UC-406

LBL-28700

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the 1990 International Industrial Symposium
on the Supercollider 2, Miami Beach, FL, March 14–16, 1990,
and to be published in the Proceedings

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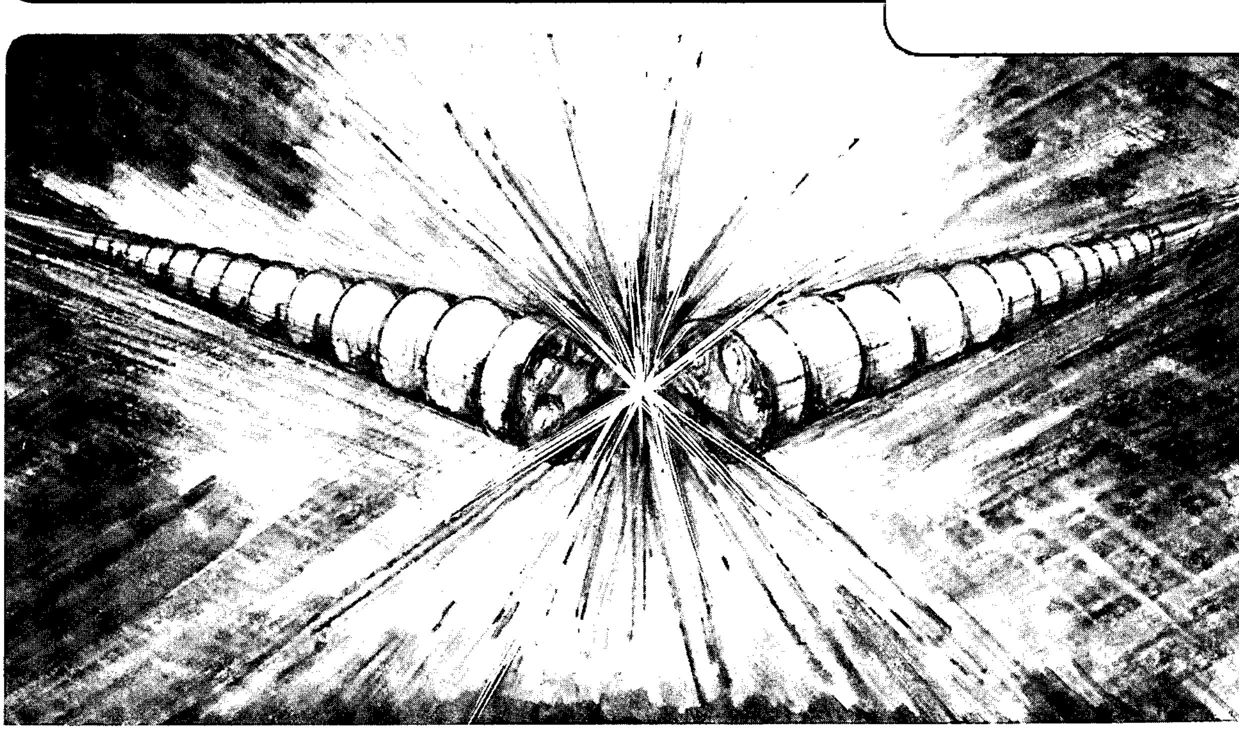

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

SC-MAG-280
LBL-28700

EVALUATION OF SSC CABLE PRODUCED FOR THE MODEL DIPOLE PROGRAM DURING 1989 AND THROUGH FEBRUARY, 1990*

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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Sciences, Divison of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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ABSTRACT

During 1989 and the beginning of 1990, approximately 150,000 feet of cable was manufactured for use in the SSC Model Dipole Magnet Program. The wire for the cable was made to SSC specifications by three different manufacturers. The cable was made at New England Electric Wire on the SSC Production Cabling Machine, under supervision of either SSC Laboratory personnel or the wire manufacturer's representative. All the cable produced for SSC model dipoles was subjected to rigorous inspection in order to insure that the magnet construction and performance would be predictable. The cable dimensions were measured at intervals of 10 feet or less with a cable measuring machine. Electrical properties were measured on samples from one end of each cable length. Critical current degradation due to cabling was checked by measuring the critical currents of the wires used to make the cable and comparing these with the cable critical current. The results of the dimensional and electrical measurements will be discussed and compared with the SSC specification requirements.

INTRODUCTION

During 1989 and through February 1990, a considerable amount of experience and knowledge has been gained in the fabrication of SSC type cable. The use of the newly developed cabling machine and the in-line measuring system has allowed the production of SSC cable to be more accurately and continually monitored. This development , together with the existing test procedures, has resulted in an expanded database[1] and better understanding of the cabling process and parameters.

CABLE TESTING

Electrical testing of SSC cable is done at Brookhaven National Laboratory in a specialized testing facility. A detailed description of the electrical testing of SSC cable is beyond the scope of this paper; only a skeleton account of the procedures are included here. We refer the reader to Reference 2 for a more complete discussion of the methods used in testing the electrical properties of SSC cable.

*This work is supported by the Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, Dept. of Energy under Contract No. DE-AC03-76SF00098.

Samples of the cable and strands incorporated into the cable are sent to BNL. Representative samples of uncabled strands are tested for I_c at various fields. The results of these strand tests are used in the determination of cabling degradation and can also exhibit a reasonable estimation of the performance of the cable[2]. Calculation of the cable degradation was done somewhat differently in this report due to the retrospective availability of wire data. Cable degradation is discussed at length in a later section of this paper. Because production scale testing allows only for a few measurements of the cable specimen, the full I_c vs. B curve of the cable is fitted using the slope of the wire curve (averaged from all wire samples tested). Previous experiments have showed that the two slopes agree well and the resulting accuracy is about ± 150A.[2] All critical current measurements are done at a temperature of approximately 4.35K because of the increased pressure due to the forced flow cooling throughout the test magnet. All reported values of the I_c are calculated for the reference temperature of 4.22K.

Resistance measurements are made on the cable at room temperature (R295) and at 10K (R10), and the Residual Resistance Ratio calculated (RRR = R295/R10). The copper to superconductor ratio is determined from these resistance values, and in turn the Cu/sc is used in calculating the critical current density (J_c) of the cable.

The mechanical testing of cable is just as important as the electrical measurements to ensure a reliable magnet. The dimensional control of the cable is monitored by the Cable Measuring Machine. The CMM is an in-line device that periodically (currently 10 ft. intervals) measures the cable width, mid-thickness, and keystone angle as the cable is being produced. A series of tests and spot-checks are performed before each cable run. These tests examine the residual twist of the cable, as well as the surface quality, lay pitch, lay direction, and bare filament integrity.[3,4]

SSC WIRE

Superconducting wire is the single most important component of the SSC cable fabrication process, therefore a short outline of the wire properties and parameters are included.

SSC Outer Wire (Table 1a)

Billet #	Total Length	Length > 10K	%L > 10K	Norm I_c (5.6T)
2071-1	264,889	227,419	85.90	292.85
2071-2	231,260	150,273	65.00	294.65
2128-1	260,767	230,094	88.20	296.15
2128-2	183,216	183,216	100.00	298.81
2128-3	340,232	331,417	97.40	302.68
B0359	392,120	332,120	84.70	310.00
B0397	388,581	337,882	87.00	313.99
2301-1	392,151	360,285	91.90	281.07

SSC Inner Wire (Table 1b)

Billet #	Total Length	Length > 10K	%L > 10K	Norm I_c (7T)	Type
2127-1	216,231	168,601	78.00	334.37	1.5
B0309	237,115	155,934	65.70	365.90	1.5
B0310	232,753	165,464	71.00	353.37	1.5
2300-1	183,652	138,414	75.40	355.51	1.5
2346-1	261,218	240,046	91.90	364.28	1.3
2346-2	264.232	224,173	84.80	366.07	1.3
2346-3	160,694	35,568	22.10	361.41	1.3

Tables 1a and 1b list the data used in constructing Figures 1a and 1b and Figures 2a and 2b. Total length is the length of wire shipped for cabling after meeting SSC specifications. The I_c reported here for these billets is the sum of the critical currents of each piece normalized with its length. This means that a long piece will have a larger contribution to the total normalized billet I_c than a short piece. Mathematically, the normalized I_c for a billet is:

$I_{ctot} = \Sigma I_{cx} l_x / L$ where L = total length
I_{cx} = piece critical current
l_x = piece length
I_{ctot} = normalized billet critical current

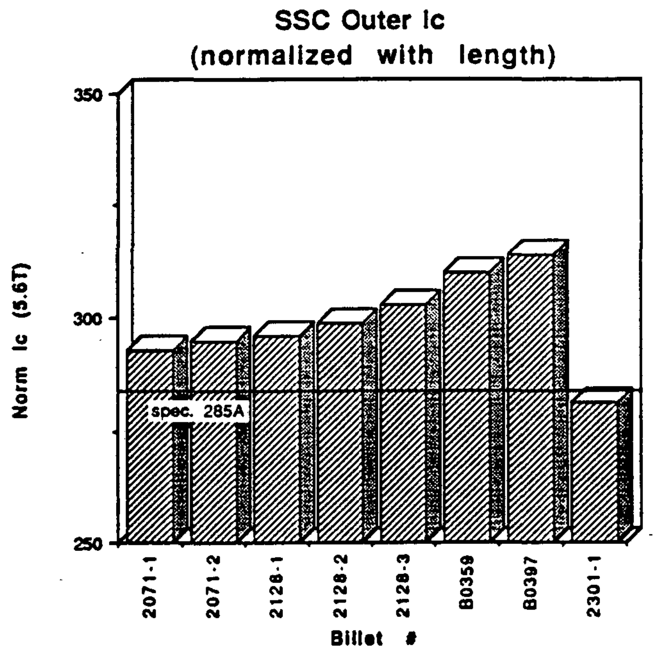

Figure 1a

Figure 1a shows the illustration of how well each SSC outer billet has performed against the SSC critical current specification. In all cases except one this requirement was comfortably met. Although billet 2301-1 fell slightly below the I_c specification for SSC wire, a low degradation during cabling allowed this material to produce acceptable cable.

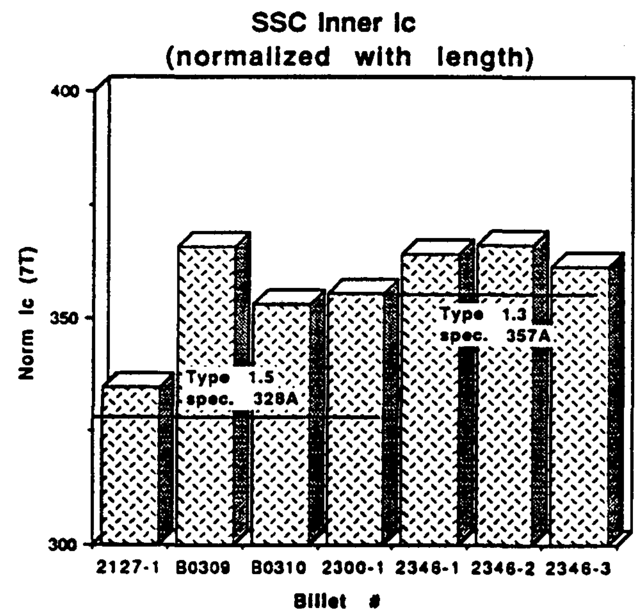

Figure 1b

Figure 1b is the equivalent of 1a for SSC inner billet data. All seven billets represented here meet the SSC specification. However, the four with a Cu/SC ratio of 1.5 exceed the minimum specified I_c by a larger margin.

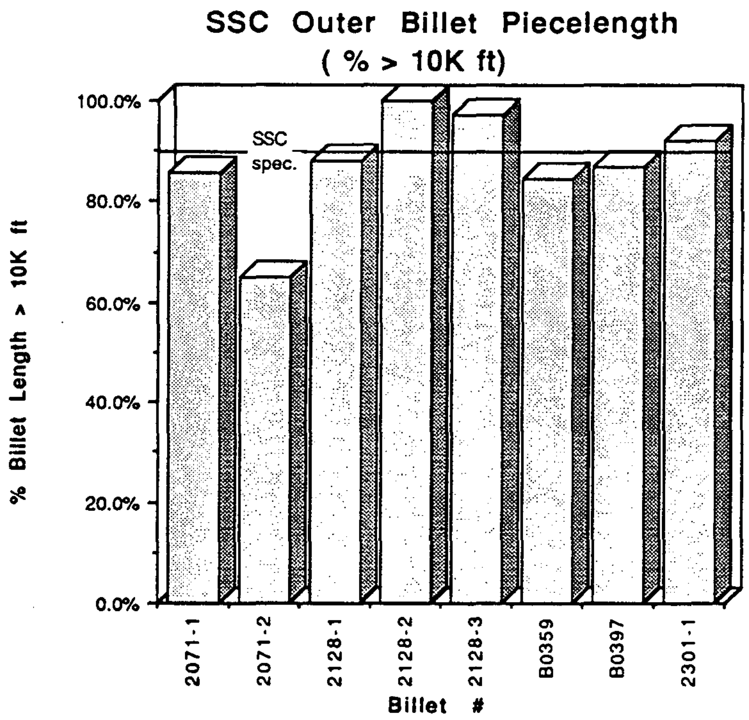

Figure 2a

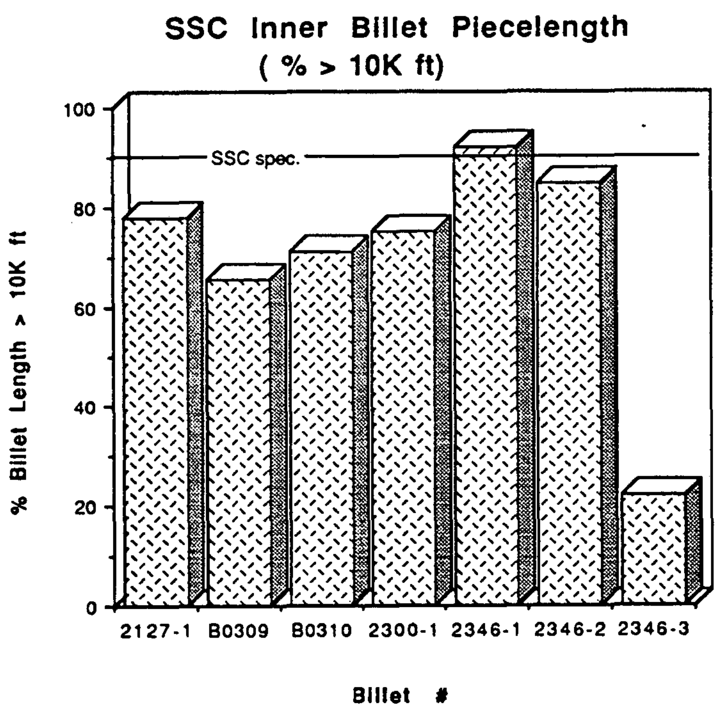

Figure 2b

Figures 2a and 2b show the piece length performance of acceptable strand from each billet. It is obvious that very few billets actually meet the proposed SSC requirement of 90% > 10,000 feet. As more experience is gained in making SSC conductor, it is expected that this piece length problem will be rectified. Piece length is only one facet of the picture however. To get a better idea of billet performance, the overall yield (total length) must also be considered. For example, billet 2128-2 has 100% of its acceptable lengths greater than 10,000 feet. Yet the sum of all acceptable lengths only reaches 183,216 feet. Depending upon the initial size of the assembled multifilament billet, this yield could be as low as 50%. Further information must be acquired from the wire manufacturer in order to clarify this point.

SSC PRE-PRODUCTION CABLE

Pre-Production cable is considered to be cable made with the "main line" SSC conductor. This is the wire fabricated to meet the existing SSC wire specification document.[3] Wire designed to address a specific issue for research purposes is considered R&D and is briefly discussed in a later section.

SSC Outer Pre-Production Cable (Table 2a)

Cable #	Length	I_c (5T)	I_c (5.6T)	Deg.	Material Inc.
SSC22-00004	13,075	9516	8338	7.10%	2128-1,2,3
SSC22-00005	13,623	9800	8608	3.40%	2071, 2128
SSC22-00006	11,000	9661	8488	4.70%	2071, 2128
SSC22-00007	4,400	9247	8138	7.60%	2071
SSC22-00008	11,091	9216	8135	3.50%	2301-1
SSC23-00001	11,800	NA	NA	NA	B0359
SSC-O-I-00002	11,267	NA	NA	NA	B0397
Total Length =	**76,256**				

Table 2a shows the SSC outer type pre-production cable fabricated in 1989 and 1990 to date. The minimum I_c at 5.6T is specified to be 7860A. The column labeled "Material Inc" shows the material incorporated into each cabling run, thus the cable performance can be referenced back to the appropriate billet and comparisons can be made.

SSC Inner Pre-Production Cable (Table 2b)

Cable #	Length	I_c (7T)	Deg.	Inc. Material	Type
SSC12-00001	5,336	7465	2.90%	2127-1	1.5
SSC12-00005	3,613	7407	3.70%	2127-1	1.5
SSC12-00007	7,100	7822	4.30%	2300-1	1.5
SSC-I-S-00008	7,894	8094	3.30%	2346-1,2,3	1.3
SSC-I-S-00009	8,935	NA	NA	2346-1,2,3	1.3
SSC-I-S-00010	10,800	8368	0.00%	2346-1,2,3	1.3
SSC-13-00003	8,572	7840	3.50%	B0310	1.5
SSC-I-I-00003	NA	NA	NA	B0309	1.5
Total Length =	**52,250**				

Similarly, Table 2b lists the SSC inner type pre-production cable for the same period. The minimum I_c at 7T is 7231A for type 1.5 cable, and 7860A for type 1.3 cable[3] (Type 1.5 designates the use of wire with a 1.5:1 copper to superconductor ratio, and likewise type 1.3 uses 1.3:1 Cu/sc strand). Also included in Tables 2a and 2b is the total footage of production outer (76,256) and inner (52,250) cable made during this period.

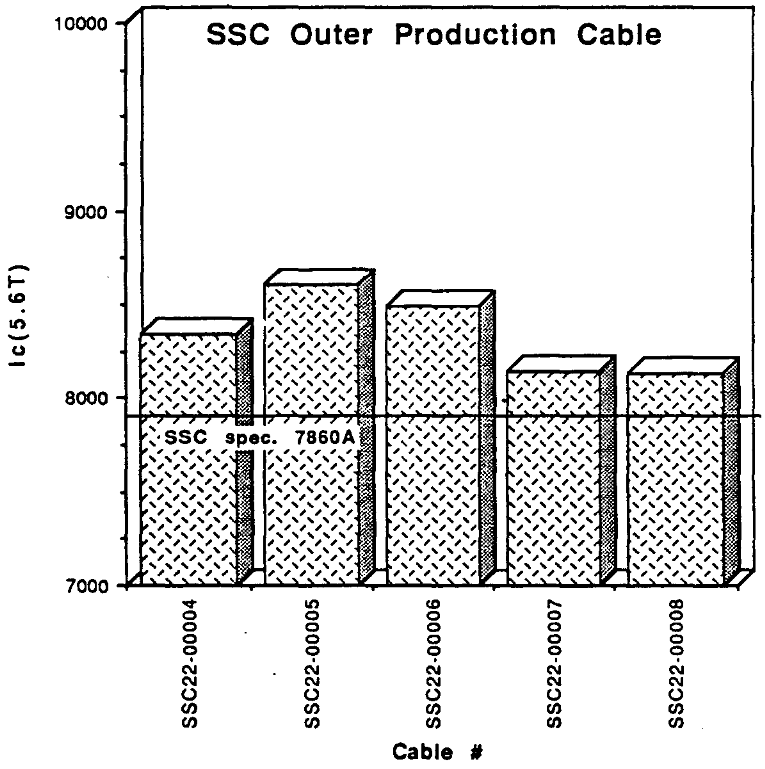

Figure 3a

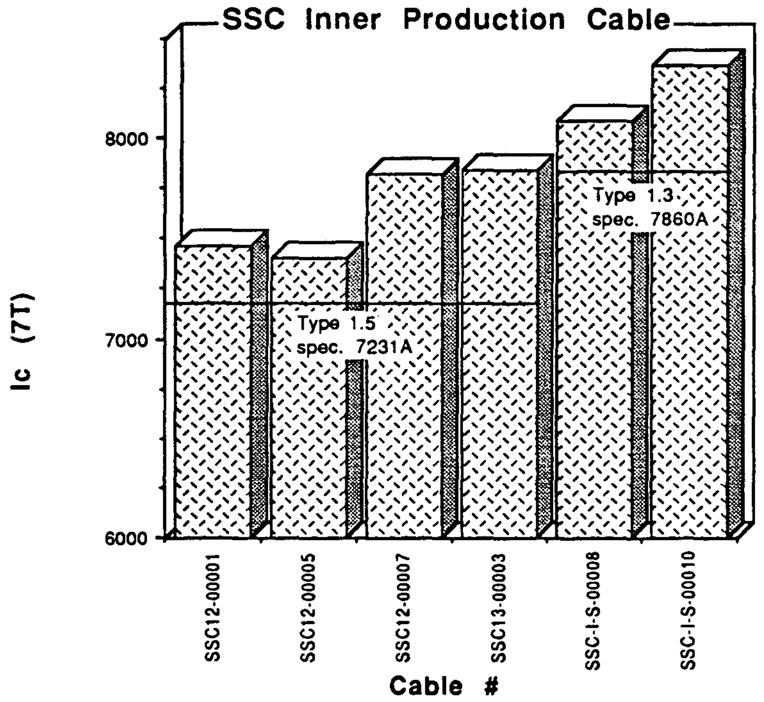

Figure 3b

Figures 3a and 3b show a bar chart plot of the I_c for the outer and inner cable that have been measured to date.

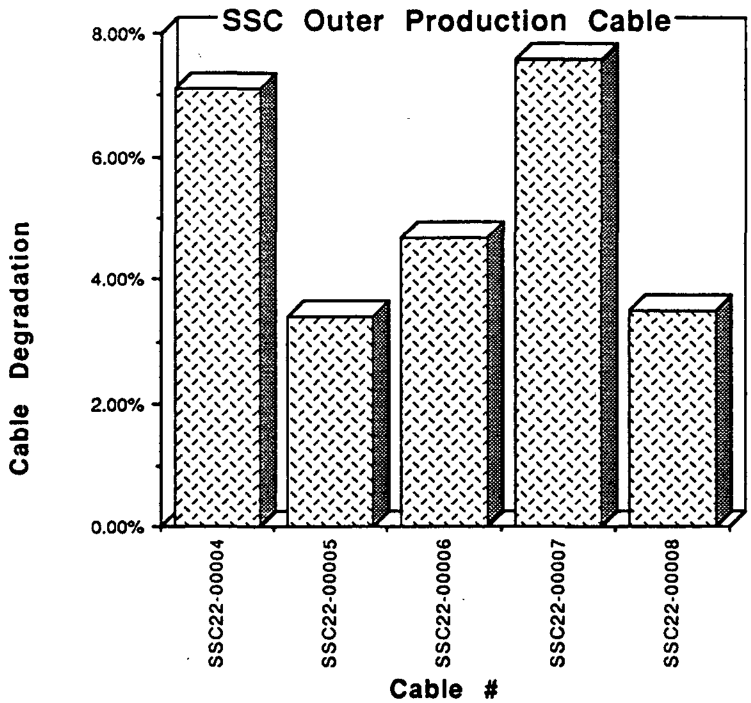

Figure 4a

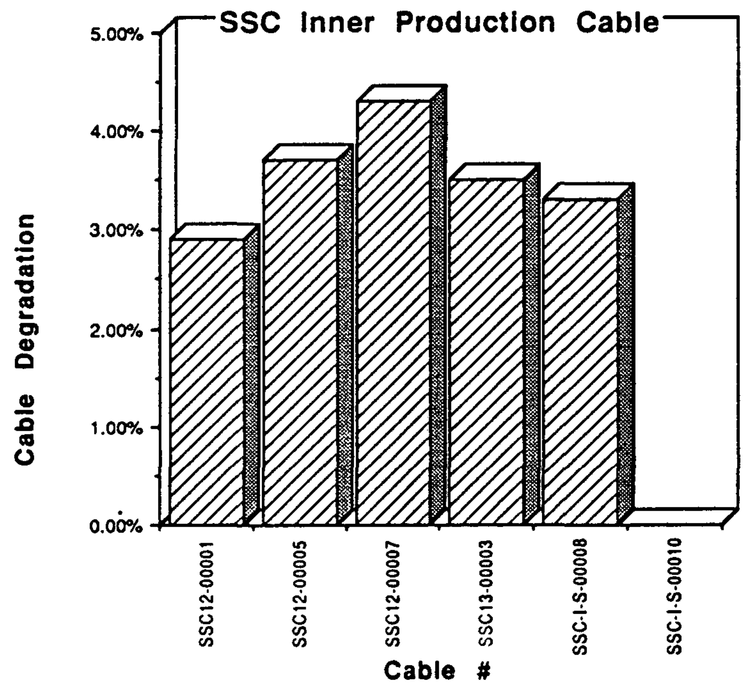

Figure 4b

The degradation values listed in Tables 2a and 2b, and illustrated in Figures 4a and 4b, show the approximate decrease in current carrying properties of the cabled strands after experiencing the deformation introduced in the cabling operation. These values are computed by using the normalized I_c numbers of the material involved in the corresponding cabling run. This is multiplied by the number of strands in the cable (23 for inner, 30 for outer) and divided into the reported I_c of the cable. The result of this quotient is subtracted from 1.0 giving the percentage of degradation induced by the cabling process. Depending upon the method used in calculating degradation, values can vary between sources. Because of the limited availability of piece length and I_c data for billets, historically the 'before cabling' I_c used in figuring degradation has been an approximation based on a few strand tests. Using the normalized I_c as is done here takes into consideration each strand used in the cable.

Cable degradation can be influenced by numerous factors, some of which can be controlled in the cabling operation. Certainly a properly aligned and properly set-up machine will help to lower degradation. This seems to be the case for cable SSC-I-S-00010 where the degradation is small enough to be lost in the error factors of the measurements. Compaction is the largest parameter affecting cabling degradation. The higher the compaction, the higher the degradation. Therefore, it is desirable to make cable at the higher end of the midthickness specification limit as long as this limit is not exceeded. This is demonstrated by a simple comparison between the degradation in cables SSC22-00005 and SSC22-00007. SSC22-00007 experienced a consistently higher compaction throughout the run which explains the higher degradation measured.

Sources of cabling degradation can also be a result of traits inherent in the strand itself. The shape and proximity of the filament array in relation to the outside diameter of the wire has been known to contribute to the amount of cable degradation. Higher degradation has been observed in strand with an insufficient amount of copper surrounding the matrix. This deficiency of copper cladding fails to protect the filaments and absorb the deformation introduced during cabling. In Figure 5 we compare the degradation in cables 12-00007, 13-00003, and 12-00001, and we can see a relative fit to the factors described

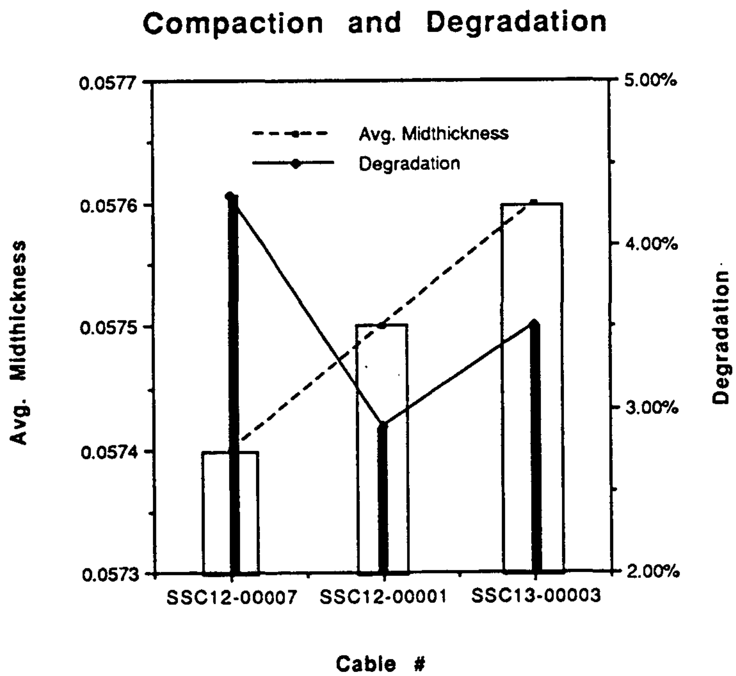

Figure 5

above. The high degradation in 12-00007 can be attributed to the higher compaction (lower average midthickness). However, if we compare 13-00003 and 12-00001, we see a reverse result. Although 13-00003 has a lower compaction, the degradation is higher. This may be attributed to the fact that strand used in 13-00003 has a cross section that is undesirable in terms of cabling degradation. The overall filamentary array has a hexagonal pattern in which the points of the hex come relatively close to the outside diameter of the strand. The problems associated with such a cross section are mentioned above.

Dimensional measurements and statistics of the cable are monitored by the Cable Measuring Machine (CMM) as the cable is being produced. Using data from the CMM, we can produce charts such as Figure 6 which shows the thickness variation throughout the entire run for cable SSC12-00005. Similar charts can be produced for keystone angle and cable width. Table 3 lists the statistics gathered by the CMM during the run.

SSC # 12-00005 In-line Cable Data (Table 3)

	PSI	Angle	Width	Thickness
Average	2547.04132	1.60452	0.36651	0.05741
Minimum	2442.00000	0.00200	0.36596	0.05727
Maximum	2467.00000	1.62700	0.36707	0.05763
Standard/Dev	2.91589	0.08448	0.00009	0.00006

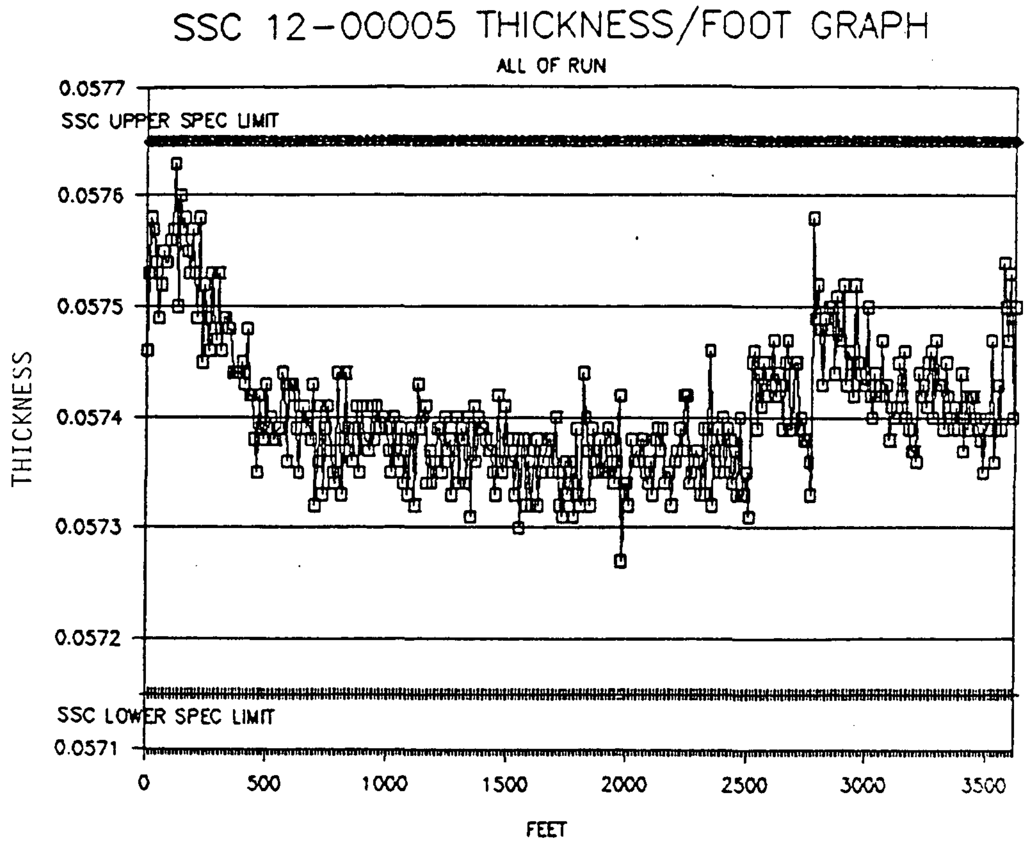

Figure 6

SSC R&D Cable (Table 4)

Cable #	Type	Length	I_c	Fil. Dia.	Notes
SSCIGC14RD	1.8 Outer	8495	NA	6um	14" dia. billet
SSC12-00003	1.5 Inner	1562	7464 (7T)	9um	Unannealed NbTi
SSC12-00004	1.5 Inner	2054	6950 (7T)	6um	Unannealed NbTi
SSC13-00001	1.5 Inner	2750	7968 (7T)	9um	0.45 LAR
SSC14-00003	1.5 Inner	1821	7464 (7T)	6um	Annealed NbTi

SSC R&D CABLE

Table 4 lists some of the R&D cable manufactured during 1989 and 1990 to date. Of considerable interest is SSC-IGC14RD. This cable is SSC outer type material incorporating strand from a 14" diameter single stack extrusion billet. This is a scale-up from the standard 12" diameter extrusion billet, and in design will improve yields and lessen fabrication costs.

Problems involving the diffusion barrier and Cu/sc ratio led to less than optimum associated properties. This first attempt at a 14" billet yielded low J_c's, piece lengths and overall yield, as well as bend test failures. It is generally believed that the reasons for this poor strand performance are known and there is confidence that future 14" billets will behave much better. Somewhat surprising, the cable Ic measurements showed less than 2% degradation with cabling.

The other R&D cables listed in Table 4 are all SSC inner type with various parameters differentiating them from production material. Cables SSC12-00003, 12-00004, and 14-00003 are comprised of strand with different filament diameter and/or different NbTi raw material history. Cable SSC13-00001 was fabricated from wire with closely spaced 9um diameter filaments. Table 4 lists the basic characteristics of these R&D cables and the length of each run.

SUMMARY

Of the total cable made during 1989 and early 1990, 76,256 feet was SSC production outer cable, 52,250 feet was SSC production inner, 8495 feet was R&D outer, and 8187 feet was R&D inner cable. In most cases the electrical values of the wire and cable fell amply above the SSC requirements. The piece lengths and yields of many of the billets, however, do not meet the present goals of the SSC project. These shortcomings are being addressed in the present manufacturing scale-up program. Cable degradation numbers have been relatively low, and increased understanding of the degradation parameters can lead to degradations consistently under 4% or better.

Throughout the past year a considerable amount has been learned about the cabling process and an initial foundation has been set for future programs, specifically the newly proposed 50mm SSC Dipole Program. The experience and knowledge developed in the 40mm magnet program will help promote a successful transition to a new cable design if required.

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