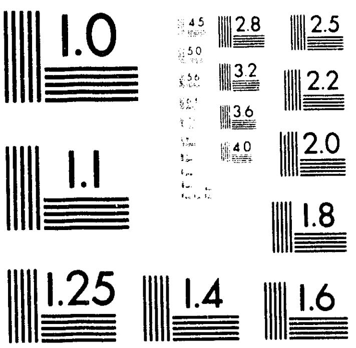
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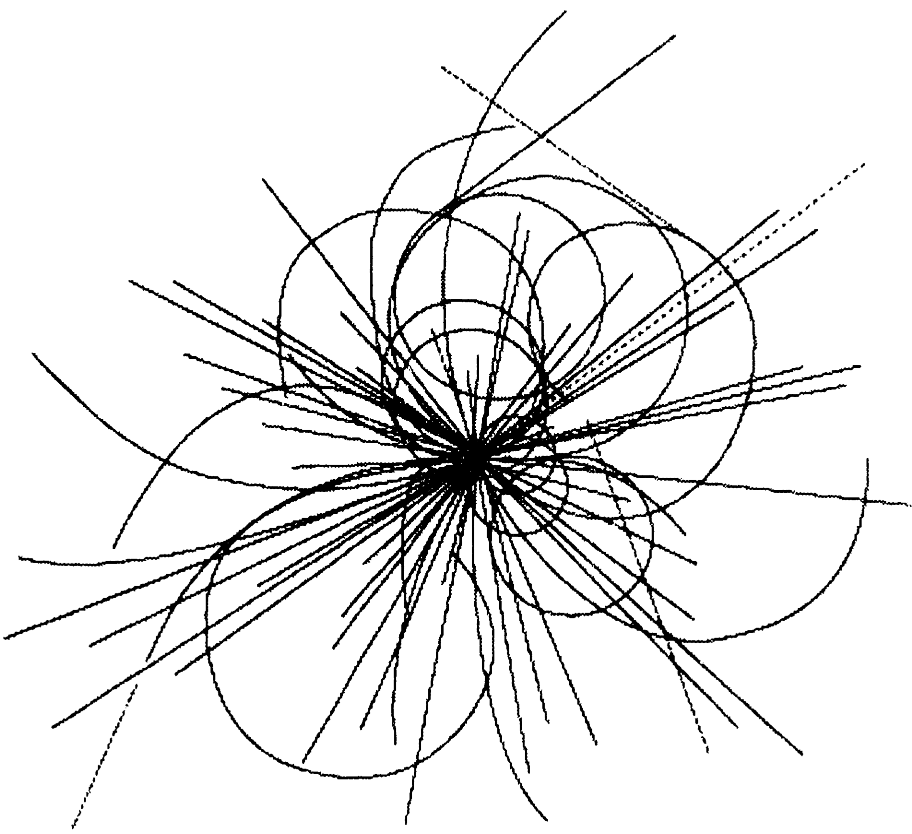

Superconducting Super Collider Laboratory

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INITIAL RESULTS OF STRAND PRODUCED IN PHASE II OF THE SSCL VENDOR QUALIFICATION PROGRAM

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INTRODUCTION

In 1991, the Superconducting Super Collider Laboratory (SSCL) instituted a program to qualify specific superconductor manufacturers for production of cable acceptable for use in both Collider Dipole (CDM) and Quadrupole (CQM) magnets. The SSCL Vendor Qualification Program (VQP) was designed with two Phases. Phase I was divided into two additional phases, IA and IB, which ran concurrently. In Phase IB, each vendor was directed to manufacture roughly 3000 kg of cable using a "baseline" process. The baseline process was agreed to by both the SSCL and the vendor at the beginning of the VQP. In this phase, process control was closely monitored with the use of statistical methods[1] and each vendor was graded based on these results. Phase IA, known as the R&D phase, was developed to allow each vendor an opportunity to optimize and improve on their baseline process in terms of both cost and manufacturability. In this phase, multifilament billets were designed to explore several key variables such as alternate alloy sources, process modifications and improved billet designs. At the end of Phase I, the results from both IA and IB were evaluated at a review between the SSCL and each vendor, and a final Phase II process was generated and fixed using the best results. In Phase II, each vendor is required to manufacture roughly 6000 kg of superconducting cable under a firm fixed price contract which can then be used to create an accurate price estimate for competitive bidding on the full rate production CDM and CQM contracts. Participating vendors include Alsthom Intermagnetics (AISA), Outokumpu (OTU), Oxford Superconducting Technology (OST), Hitachi (HIT), and Furukawa Electric (FEC) for outer cable, and Intermagnetics General Corporation (IGC), Teledyne SC (TSC), and Sumitomo Electric (SEI) for inner cable.

At the end of Phase II, each vendor must meet the minimum requirements outlined in the contract to become a qualified superconducting cable supplier. For one requirement, critical process variables identified by the SSCL Conductor Department at the beginning of the VQP will be evaluated to determine the quality and uniformity of the material produced during Phase II of the program. Variables considered critical are steady state Cu/SC ratio, final wire diameter, critical current and RRR in strand, and keystone angle, width, mid-thickness, twist, pitch and critical current in the cable.

* Operated by the Universities Research Association, Inc., for the U. S. Department of Energy under Contract No. DE-AC35-89ER40486.

Preliminary results are reported with emphasis on Phase II strand produced by each of the eight vendors in the VQP. Analysis of the critical electrical and mechanical properties of the strand are presented, with discussions concentrating on the statistical variation and process control of each vendor. The piece length and yield statistics of the final strand are also examined.

STRAND PERFORMANCE

In the early stages of SSCL-type superconductor development, a major obstacle to overcome during the manufacture of both inner and outer strand was piece length. During the Accelerator System String Test (ASST) program, most wire manufacturers participating in the VQP were consistently achieving average piece lengths from 1500 to 4000 meters.[2] For Phase II of the VQP, preliminary data shows that for most vendors, piece lengths have dramatically improved over ASST results for both inner and outer strand as can be seen in the distributions, average piece lengths and mass median piece lengths shown in Figure 1. Seuntjens, et al, has shown that if a mass median piece length of 10,000 m for inner or 15,000 m for outer is attained, strand to cold weld free cable yields of approximately 97% would be expected.[3] The baseline cost estimate target cable yield of 94% would then be feasible assuming losses due to strand breaks, crossovers,etc., do not exceed 3%.

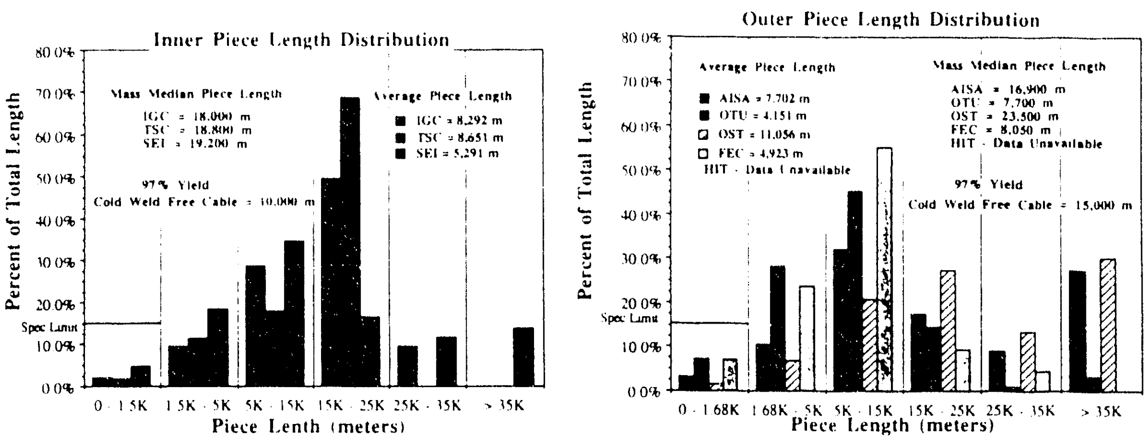

Figure 1. Length distribution, average piece length, and mass median piece length for inner and outer wire manufacturers.

In addition to piece length, multifilament yield has a large impact on the cost of the final cable. SSCL's baseline cost estimate target value which was generated at the beginning of the program assumed a 90% yield for multifilament billets. Preliminary results show that most vendors are making adequate progress towards meeting this value (see Table 1).

Table 1. Percent of Phase II completion, percent yield and coefficient of variation of multifilament billets for inner and outer wire manufacturers.

	VENDOR	% Complete	% YIELD	CV %
OUTER	AISA	100	85.3	2.9
	OTU	100	79.2	3.2
	OST	100	85.1	2.6
	FEC	30	81.3	0.4
	HIT	6	92.1	3.4
INNER	IGC	17	84.0	1.3
	TSC	14	79.0	1.4
	SEI	60	87.7	1.4

In Phase I of the VQP, Cu/SC ratio was the most difficult parameter to control with most manufacturers having performance index's[1] (C_{pk}'s) between 0.5 and 1. Phase II results were similar to Phase I with Cpk's remaining near 1 for most vendors as seen in Figure 2. High Cu/SC ratio variation is an inherent problem in the superconducting wire production process due to unsteady state material created at both ends of the billet during the multifilament extrusion. One method to increase Cpk would be to scrap acceptable material from the ends thereby reducing the standard deviation of the population. This, however, would cause a dramatic reduction in billet yield. To resolve this problem, SSCL will evaluate this parameter during qualification only in the completely steady state region. Figure 2 shows the data including the unsteady end effect material to make comparisons to Phase I meaningful.

A box plot showing the range of I_c for each manufacturer along with the coefficient of variation[1] (CV) for the data are shown in Figure 3. This I_c data was generated by production unit testing which was implemented for Phase II. The production unit test method for I_c requires that the Cu/SC ratio be determined for each piece of wire in a production unit, and I_c tests performed on any three pieces of wire with the average Cu/SC in that production unit. From the figure, you can see that the CV's for all vendors is 2% or less which is similar to the Phase I and ASST[2] results. Based on this, one can conclude that production unit testing gives an accurate interpretation of the average I_c of a production unit without testing every piece of wire. In addition, extracted strand I_c results from Phase IB cable show CV's of less than 2%[4] which confirm that the need for strand mixing in the cable based on I_c's is unnecessary to achieve low CV's in cable.

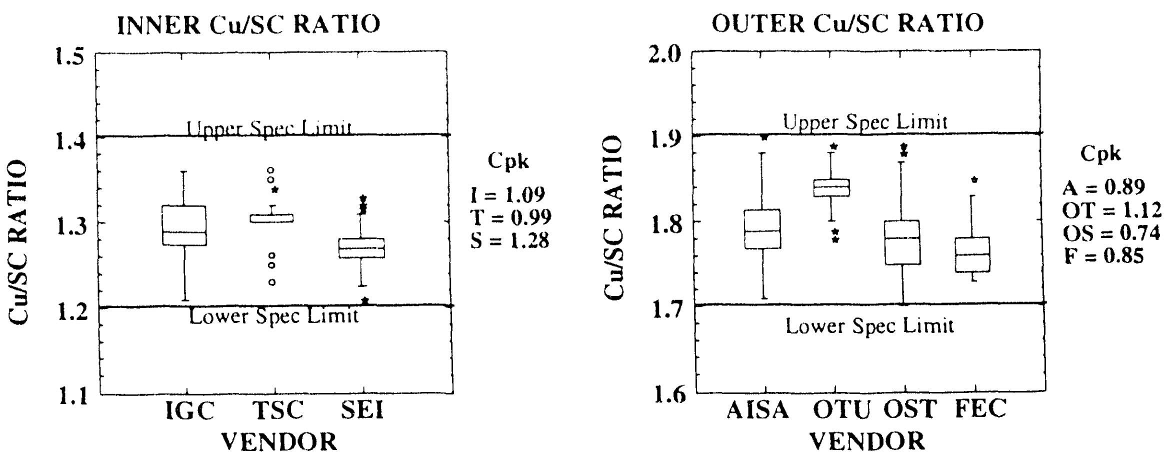

Figure 2. Box plot and performance index of Cu/SC ratio for inner and outer wire manufacturers.

The box plot and C_{pk}'s of the strand diameter data from Phase II is shown in Figure 4. All manufacturers were extremely successful at controlling this parameter with Cpk's well over 1.5. This equates to less than 6 strand diameter nonconformances per 1 million data points.

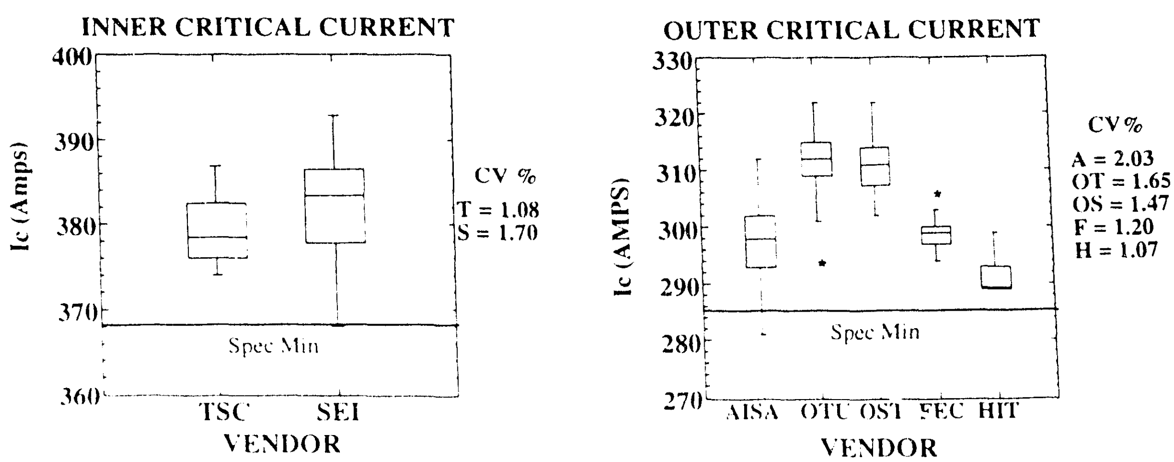

Figure 3. Box plot and coefficient of variation of I_c for inner and outer wire manufacturers.

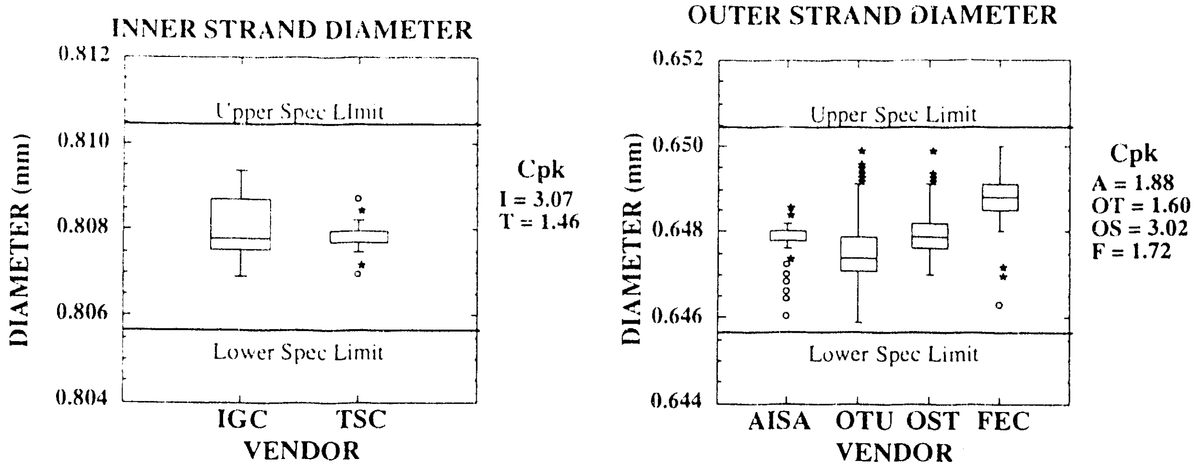

Figure 4. Box plot and performance index of strand diameter for inner and outer wire manufacturers.

SUMMARY

In Phase II of the VQP, each manufacturer was required to produce roughly 6000 kg of cable. Piece length has dramatically improved over ASST results for most vendors making cold weld free cable with strand to cable yields of approximately 97% expected. Most vendors are making adequate progress towards the baseline cost estimate target value of 90% for multifilament billet yield. The Cu/SC results are similar to Phase I resulting in C_{pk}'s of around 1 for most manufacturers. I_c results using production unit testing achieved CV's of 2% or less which is comparable to ASST and Phase I results. This substantiates that production unit testing gives an accurate interpretation of the average I_c of a production unit without testing every piece of wire. The variation of strand diameter is very low with manufacturers achieving C_{pk}'s consistently greater than 1.5.

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