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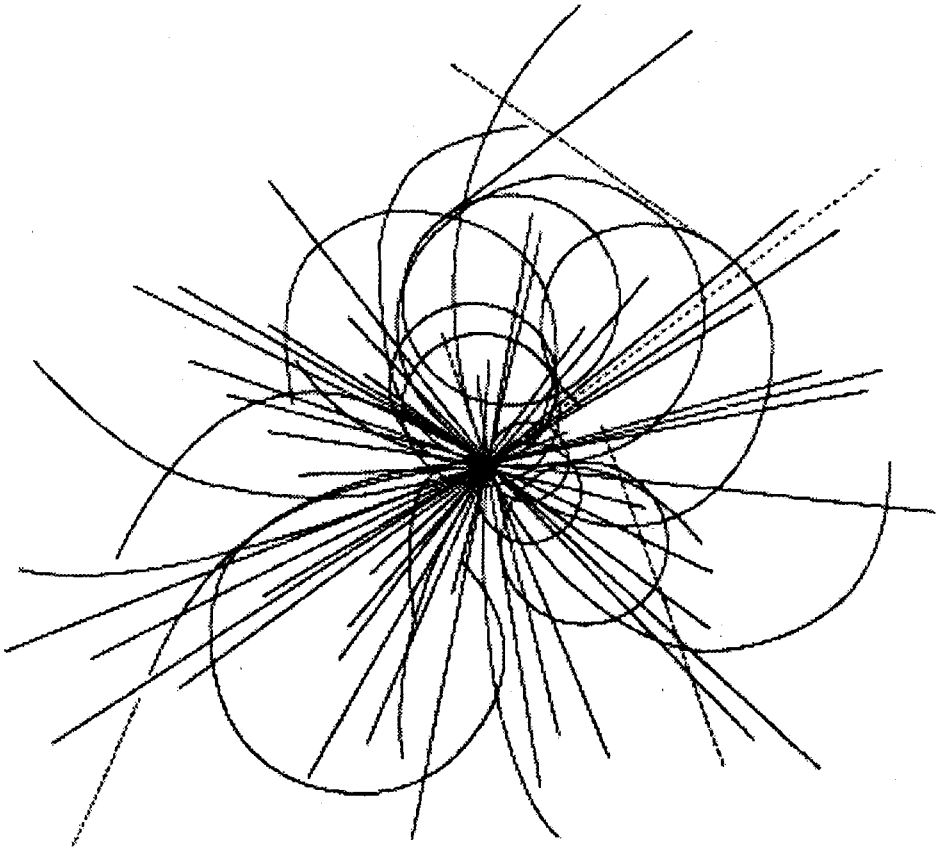

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RESULTS OF CABLING FROM PHASE IB OF THE SSC VENDOR QUALIFICATION PROGRAM

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INTRODUCTION

The Superconducting Technology Department of the Superconducting Super Collider Laboratory (SSCL) is directing the Vendor Qualification Program (VQP) to identify vendors of superconducting material to fabricate 6-micron filament conductor for various magnet programs. Eight suppliers are participating in the qualification program: Intermagnetics General Corporation, Inc. (IGC), Teledyne SC (TSC), and Sumitomo Electric Industries (SEI) are fabricating 30-strand inner cable and Oxford Superconducting Technology (OST), Furukawa Electric Co. (FEC), Hitachi Cable, Ltd. (HIT), Alsthom Intermagnetics, s.a. (AISA), and Outokumpu Copper Superconductors (OTU) are fabricating 36-strand outer cable. Phase I of the VQP included two portions: Phase IA, the R&D portion, and Phase IB, a simulated production quantity processed on a single production process. During Phase IB of the VQP, each of the suppliers was to fabricate approximately 3500 kg of finished cable, meeting the appropriate cable specification. This cable is being used to manufacture the prototype magnets in each of the major magnet programs underway within the Magnet Systems Division. In order to meet the needs of the Collider Quadrupole Magnet program, four of the five outer cable vendors were directed to divert approximately 350 kg of finished strand to the fabrication of 30 strand quadrupole cable.

Each vendor was responsible to direct the cabling activities for his own material. Four vendors (IGC, SEI, FEC, and HIT) chose to perform the cable manufacturing on machines at their own facilities. The other four chose cabling subcontractors; OST and OTU cabled at New England Electric Wire Corp. (NEEW), and AISA and TSC cabled at Superconducting Cabling and Engineering, Inc. (SCE).

CABLE SUMMARY

Cabling Yield. All vendors began Phase IB with the plan to complete the full quantity of 3500 kg. The planned quantity of inner cable was reduced to 3150 kg due to a change of Cu/SC specification at the beginning of the program. The finished amount was a result of both the yield of the wire processing and the cable manufacturing. The results in Table 1 only represent yields of the

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Table 1. SSC cable data from extracted strand measurements performed at the SSCL. Reported I_c values correspond to testing fields of 7 T for inner and 5.6 T for outer and quadrupole cables, at temperature of 4.22 K.

Vendor	Type	Quantity (meter)	Cabling Yield (%)	Cable I_c (Amp)	Cable I_c CV (%)	Ave Deg. (%)	J_c Slope ($A/mm^2/T$)	Slope CV (%)
IGC	Inner	25,841	78%	11,113	1.66	3.51	567	3.0
SEI	Inner	15,807	76%	10,822	1.45	3.75	539	1.7
TSC	Inner	231	--	11,233	--	4.02	578	--
OST	Outer	28,393	88%	10,538	0.93	3.96	569	1.7
FEC	Outer	26,046	88%	10,564	1.20	0.36	607	0.9
HIT	Outer	14,216	56%	10,179	1.42	6.83	552	1.6
AISA	Outer	26,126	82%	10,399	0.29	1.36	571	0.8
OTU	Outer	18,995	87%	10,968	0.81	3.65	618	1.5
OST	Quad	4,691	--	8,672		5.35	552	
FEC	Quad	4,456	--	8,750	0.99	1.1	597	0.4
AISA	Quad	4,698	--	8,593		2.61	558	
OTU	Quad	4,571	--	9,023	0.62	3.3	598	1.2

strand-to-cable portion of the process. The total length of within-specification strand was compared to the length of the delivered cable multiplied by the number of strands in the cable. The baseline expected yield before beginning the program was 91%, which includes an approximate 4% loss due to the lay pitch of the strand in the cable. Many extra losses occurred during Phase IB, including extra material used for cable startup, crossovers and strand breaks, and mishandling of the cable being wound onto spools.

Critical Current. In Figure 1 the critical current results of the cables from each supplier are compared. The results are from extracted-strand testing done at the SSCL. A specific explanation about the extracted-strand testing can be found in an accompanying paper by Kovachev[1]. The cable-to-cable coefficient of variation (CV, where CV = standard deviation, σ, divided by the mean, $\overline{X}$) within any one supplier is no greater than 1.7%. This variation compares to maximum CV of 1.5% within the cable batches produced for the Accelerator System String Test (ASST) in 1991[2]. Taken as a whole, the entire population of inner cables have an average I_c of 11,035 A, with a variation of 1.99%. CDM outer cables average 10,538 A, with 2.26% variation, and CQM cables showed an average of 8,834 A, with 2.17% variation.

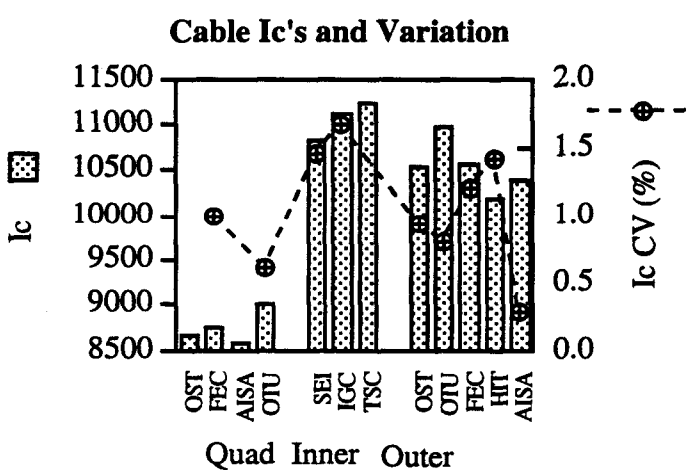

Figure 1. Average Critical Current and Coefficient of Variation for each cable batch. Specified Ic's are 8,160 A 10,500 A, and 9,780 A for Quad, Inner, and Outer cables respectively.

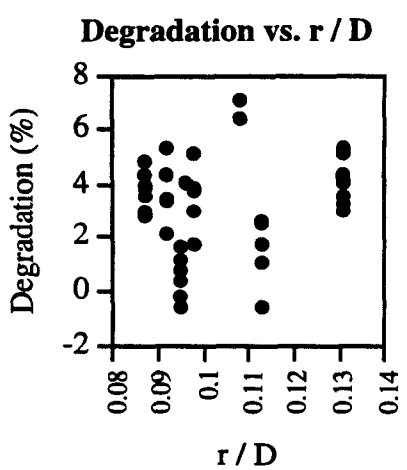

Figure 2. Extracted Strand Degradation factor versus r / D ratio for each vendor's strand.

Degradation. Previous summaries of cable results have indicated that the degradation in the cable has correlated strongly with a parameter of the superconducting strand geometry called "r / D"[3]. This r / D parameter is a ratio of the minimum thickness of the copper jacket around the filament array (r) to the outside diameter of the finished strand (D). Outer-type cables used in the ASST particularly indicated that by using a thicker copper jacket around the filament array, and therefore increasing the r / D ratio, the cabling degradation could be reduced. Figure 2 displays a plot of measured degradation versus r / D for the cables in Phase IB. In this case no correlation can be drawn between the parameters. Cables for previous SSC programs have been electrically tested at Brookhaven National Laboratory, in the full cable state. The procedure for those tests included a mathematical correction for the self field of the cable[3]. When the degradation was calculated, it was then possible to achieve negative degradation factors. In the extracted strand testing procedure, randomly selected strands were extracted from the cable, and tested individually. The average critical currents of the extracted strands were compared to the average critical currents of all the strands in the cable as reported by the manufacturer. Because the extracted strands are tested in the same magnetic conditions as the precabled wires, the reduction in current is a true degradation factor. Because the wire may be further deformed by handling in preparation for testing, this degradation is a worst case estimate of the true degradation.

J_c vs. Field Slope. The J_c slope was calculated using the ratios of the extracted strand J_c's at 7 T and 8 T for inner and 5.6 T and 7 T for outer cables. The average slope has a range of 15% between all of the vendors. Most have a variation near 2%. Observations from Phase I of the VQP program are that while a vendor can consistently produce a certain J_c slope, process variables are so interrelated that it is difficult to adjust this to a target value.

CABLE DIMENSIONS

During Phase IB of the VQP, the ability of each cable supplier to maintain control of the cable dimensions was evaluated by the statistical index called Process Capability Index (C_{pk}). C_{pk} is defined as:

$$C_{pk} = \frac{\mathrm{Min}[(\overline{X} - LSL), (USL - \overline{X})]}{3\sigma},$$

where $\overline{X}$ is the mean, USL is the Upper Specification Limit, LSL is the Lower Specification Limit, and σ is the standard deviation of the data. The target C_{pk} for the VQP is 1.5, which indicates a process that will have 6.8 defects per million measurements. A typical measurement frequency during cable production is once per 3 meters of cable. A company meeting this benchmark would have one out of tolerance condition every 49,000 meters of cable. Figure 3 shows the resulting C_{pk}'s for each dimension and each type of cable.

Keystone Angle. The actual variation in the keystone angle is approximately the same for all three cable types, but because the tolerance range of 36-strand outer cable is $\pm 0.06^{\circ}$ rather than $\pm 0.1^{\circ}$, the variation is larger relative to the tolerance band, and the C_{pk}'s are generally lower.

Width. The most noticeable group of results is in Sumitomo's batch of inner cables, where Cpk ranges from 0.8 to 1.5. As the width specification is written as 12.34 +0.05, -0.00 mm, SEI targeted the nominal value of 12.34 mm. If the evaluation had been done with the index C_p, which does not take into account whether the results are centered within the tolerances, SEI would have results from 2.0 to 3.0. In comparison, IGC's results would range from 3.0 to 5.2. The other suppliers of outer and quad cable meet the expectations in nearly every case.

Midthickness. It can be seen that at this point the control of the keystone angle and width dimensions have been accomplished much better than the control of the midthickness. In comparison between the width and midthickness dimensions, both are produced by the same mechanical method using ground rollers, and therefore, the variation of both will be approximately the same. However, the tolerance range for midthickness is only 0.012 mm, one fourth of the range for the width, which is 0.05 mm. Some cases of thickness control have been demonstrated,

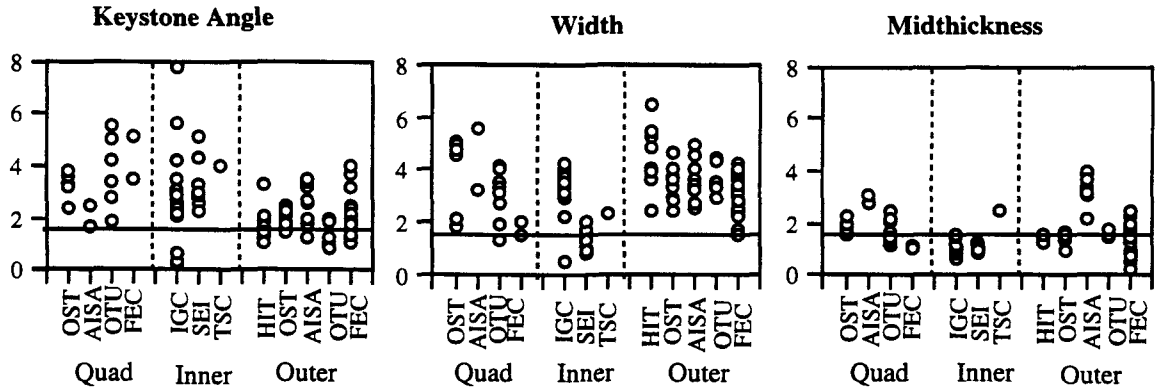

Figure 3. Process Capability Indices (Cpk's) for the dimensionsions of each cable batch, grouped by cable types.

but generally there is still improvement to be made in this area. Companies who maintained the best control generally did so by eliminating eccentric runnout of the rollers and bearings, and controlling the temperature of the turkshead unit. During the cable run, heat generated from the strand deformation warms the rollers. It has been universally observed that unless the turkshead rollers are preheated to the same temperature as during the cable run, the diameter of the rollers will increase due to the added heat, and the thickness of the resulting cable will become thinner as the run progresses. Temperature changes in the room environment can affect the thickness in the same way. In order to counter this effect, some vendors have added climate control for the turkshead and/or temperature control methods for the rollers.

SUMMARY

The number of participating vendors in the VQP program is more than in any of the previous cable programs. Electrical results and variations are comparable, but slightly more variations occur in some vendors' cases. Dimensional variations of the cable are being addressed, and in some cases variations are being controlled to the level of the program goals. The Phase IB cable does demonstrate that the SSC cable can be fabricated in uniform production batches. Points for further improvement for Phase II have been identified for each supplier, which range from yield improvement to dimensional control through specific machine parameters.

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