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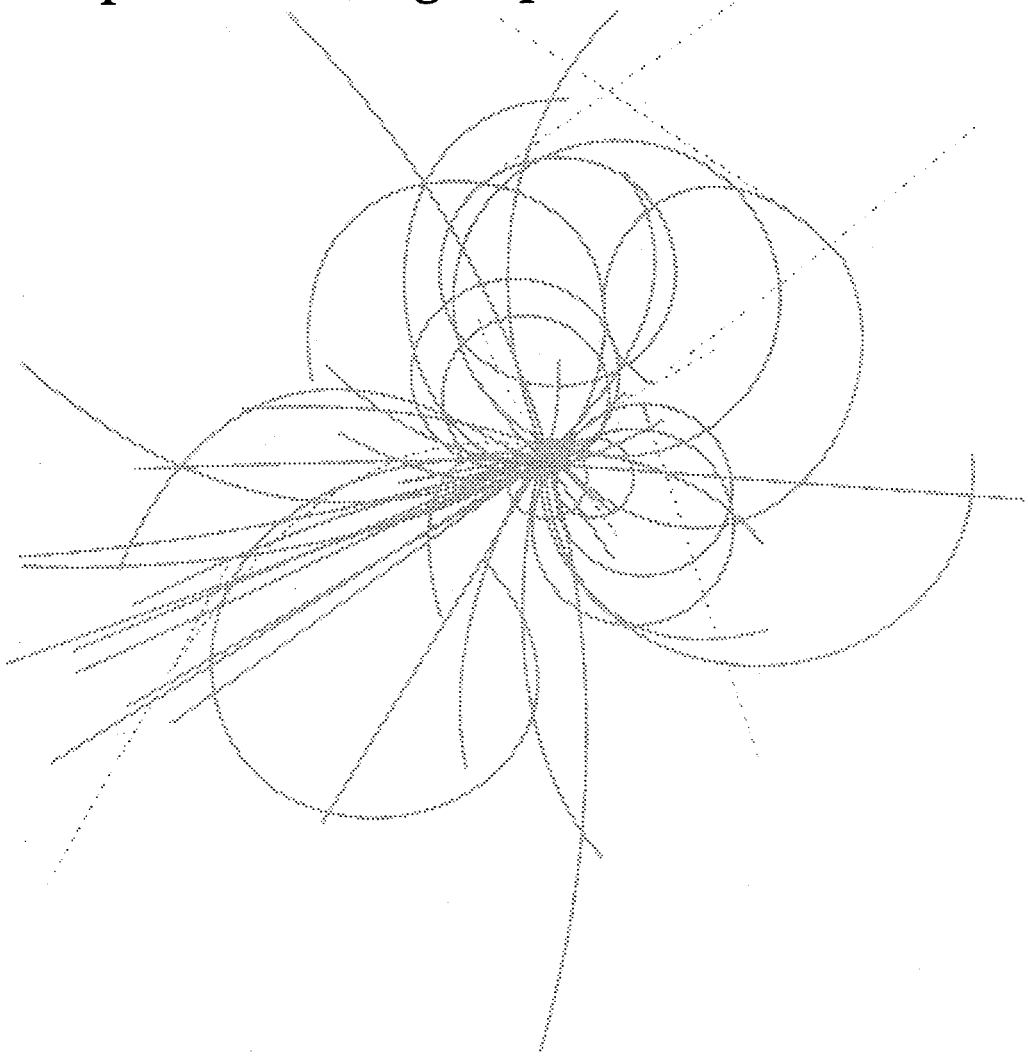

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March 1992

To be published in *Supercollider 4*

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J. M. Seuntjens, D. Christopherson,
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Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

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*Presented at the International Industrial Symposium on the Super Collider, New Orleans, March 4–6, 1992.

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

COLD WELD ANALYSIS IN SSC STRAND AND CABLE

J. M. Seuntjens, D. Christopherson, F. Y. Clark, and D. W. Capone II

Superconducting Super Collider Laboratory
2550 Beckleymeade Avenue
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INTRODUCTION

Cold welds on superconducting strands are simple joints formed by pushing two strand ends together. Cold welding is commonly used between cable runs to avoid having to rethread cable machines. However, to increase the quantity of finished strand going into cable, cold welds have been used within cable for High Energy Physics magnet coils. Although magnets have successfully been built and tested with cold welds, the presence of the cold weld increases the risk of cable failure during cable fabrication, magnet fabrication, and possibly magnet operation. A cold weld failure during the cable run is not repairable and results in the scrapping of a full-coil length of cable. The Superconducting Technology Group has experienced approximately 6 coil failures due to cold welds during the past two years in supplying cable for model and Accelerator Systems String Test (ASST) magnets for the Superconducting Super Collider Laboratory (SSCL). Four of these cold welds failed during cable manufacture. One cold weld failed during cable insulation, and another during coil winding. Cold welds that failed within the splicing between coil lengths on the cabling machine did not result in a loss of cable and were not included. The cold weld failures within the coils represents a failure rate of 6% of the coils fabricated and approximately 2% of the total number of cold welds contained.

SSC Inner and Outer cable specifications SSC-M30-000014 and SSC-Mag-M-4148, respectively, currently require coil lengths of cable to be cold weld-free for 80 m on each end. Cold welds must be a minimum of 35 m from each other, and the cold weld spacing within the same strand of the cable must be a minimum of 70 m. This removes cold welds from the pole and the mid-plane turns as well as the coil ramp splices, and separates cold welds within the wound coil. The cable length for winding of SSC dipole magnet coils are 650 m for Inner and 885 m for Outer. Therefore, the maximum number of cold welds in a magnet is 14 for Inner and 20 for Outer. Removal of the cold welds increases cable reliability at a cost in cable yield from strand. The yield penalty is strongly dependent on the strand piece length (PL).

Cornish[1] and Garber[3] have shown that cold weld joints are non-superconducting with about the same resistance as copper. If we take the resistance of the cold weld per unit area from Cornish, the resistance of a Inner cold weld is $4 \times 10^{-7}\ \Omega$. This value is equivalent to the resistance of 1.2 mm of copper of the same 0.808-mm-diameter having a RRR of 100.

This paper comprises two parts. Part 1 analyzes cold welds morphologically and mechanically. Cold welding procedures are described based on welds made at the SSCL on Inner conductor. The end preparation and the number of repetitions during the welding are varied. Part 2 analyzes the cable yield from strand vs. the strand PL to help evaluate the cost of removing cold welds from SSC dipole magnet coil lengths. A model is developed to express the yield of cable from strand based on an exponential distribution of PLs. Six batches of strand procured by SSC for the ASST are analyzed for theoretical yield to support the model.

EXPERIMENTAL—PART 1

A Huestis hand-held cold welder with 0.0318-in. (0.808 mm) dies was used for this study. IGC Inner strand number 642-1-17 was used for all cold welds. Strand ends were either pinch-cut with a Crescent 951-4 102-mm side cutter, or scissors-cut with a standard 8-in. (200 mm) office desk scissors. The procedure for cold welding has been reported previously,[1] and the previous authors' description is repeated here:

> Figure 1 shows the various stages of making the cold weld joint. In stages 1 through 3, the die inserts grip the two conductors and then press them together. The die is recessed to accommodate the extruded material. The presence of oxide and other contamination between the two butted surfaces usually prevents the formation of a bond at this stage. The dies then open and re-grip the conductor further back; the process is then repeated (stages 4 through 6). After stage 6, when the contamination has been extruded out of the joining region, the two pieces are invariably joined. To ensure a good joint, we repeat stages 4 through 6 three more times (making a total of 5 pressure applications).

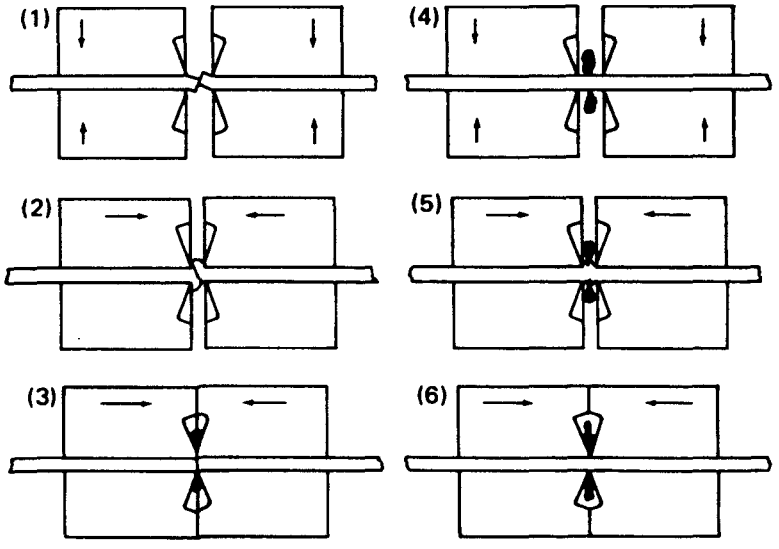

Figure 1. Steps in cold-welding process, taken from Reference 1.

Approximately 10 cold welds each were made for 2, 5, and 10 repetitions of the cold weld cycle for both pinch-cut ends as well as scissors-cut ends. Samples 5S and 10S are scissors-cut ends with 5 and 10 repetitions, respectively. Samples 5P and 10P have pinch-cut ends with 5 and 10 repetitions, respectively. In addition, pinch-cut samples with

5 repetitions were made with a single-sided razor blade inserted between the die faces to provide a 0.254-mm spacing that prevents complete die closure (sample 5PP). The travel distance for the dies during each repetition is 1.96 mm. The spacer was inserted to simulate an improper weld fabrication caused by operator error or residue flashing in the dies.

The flashing created during cold welding was bent back and forth along an arc having an axis normal to the axis of the strand. This usually resulted in a break close to the nominal strand surface. The joints were then sanded smooth with 320 grit (47 μm) sand paper. The sanding was continued only until the cold weld felt smooth to the operator's fingernail.

Cold welds were examined as formed, and after tensile testing, with a JOEL 6100 SEM. Tensile tests were made using an Instron 4302 testing machine with a gauge length of 250 mm. Custom-made 50.8 mm (2.00 in.) barrel grips were used to grip the samples using a 300° wrap. Cold welds were placed at the center of the gauge length, and tensile tests were performed at a cross-head displacement rate of 10 mm per minute.

RESULTS—PART 1

Figure 2 contains micrographs of cold welds with 5 and 10 repetitions. The flashing typically flows out in two arms approximately 180° apart. The thickness of the flashing is typically about 0.25 mm (0.01 in.). The flashing in the 5PP samples was notably thicker, as much as 0.4 mm (0.02 in.). Occasionally, the flashing extruded strongly in one direction. Figure 3 contains representative images of the cleaned surface of cold welds. After removal of the flashing, the surface of the strand is smooth with an occasional crater caused by pullout of the flashing. In some cases, the cold welds remain as much as 0.04 mm (0.001 in.) larger in diameter than the stand, and in other cases, a slight misalignment of the two strands remains. Figure 4 shows longitudinal cross sections for the same samples as in Figure 2. A 5P type sample (top) has a similar flow pattern as seen in 5S, 10S, and 10P sample longitudinal sections. Note that the material from the filaments on the top left side flow to the bottom flashing rather than the top. This does not appear to indicate a bad weld. A 5PP type sample shown in Figure 4 (bottom) contains a "dead zone" of material on the top left side.

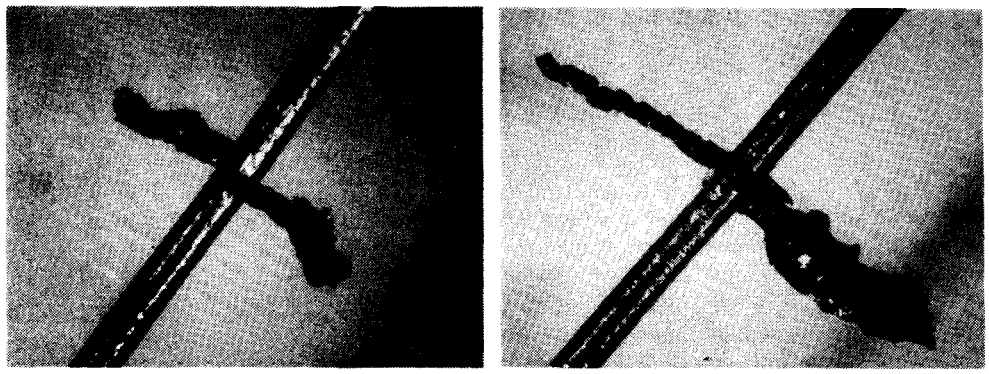

Figure 2. Light micrographs at approximately 10 × of cold welds with 5 repetitions (left) and 10 repetitions (right).

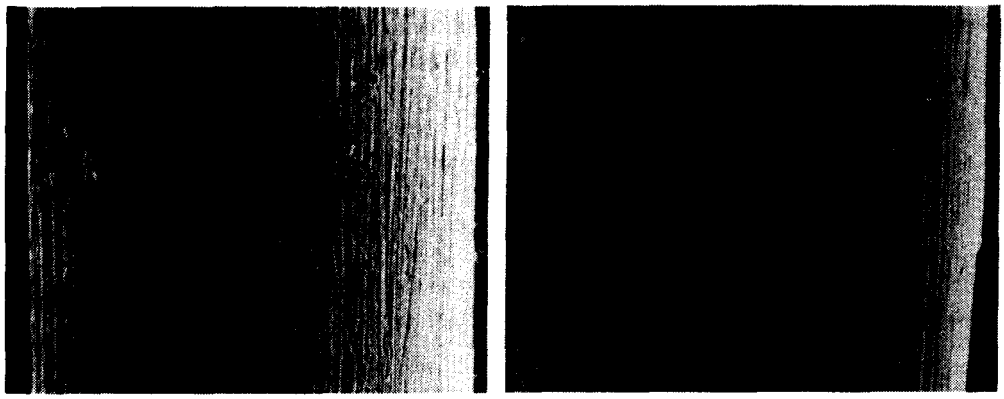

Figure 3. Surface of representative cold welds after the flashing has been removed and the surface smoothed with emery paper. Craters on the surface (left) and some misalignment of the strand going into the joints (right) are sometimes seen.

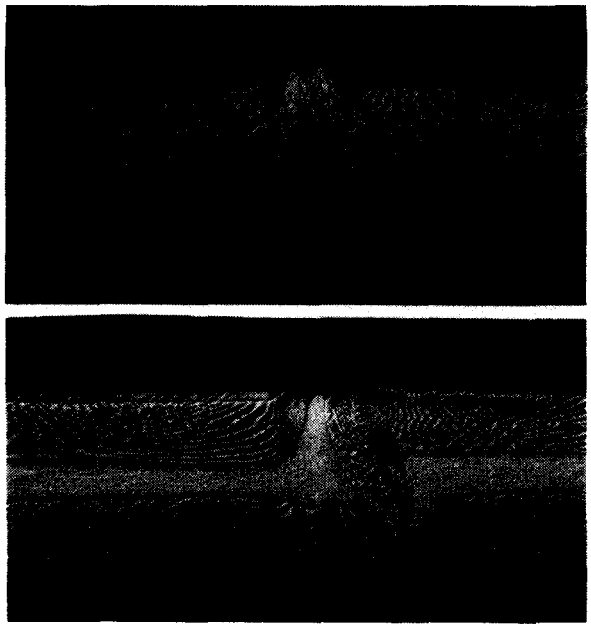

Figure 4. Longitudinal sections of representative cold welds in this study. A 5P sample (top) and a 5PP sample (bottom).

Cold welds with 2 repetitions were poorly joined. They often failed during the cleaning of the flashing, and were therefore no longer studied. Stress vs. strain curves in all cases have very similar curvature up to an abrupt failure of the cold weld. Failure strain was not studied since the strain over the entire gauge length tells little about the nature of the cold weld, which has an axial extent along the strand of approximately 1 mm. The failed cold weld shows little sign of yielding typically seen in copper tensile specimens. Table 1 shows the ultimate engineering stress of cold welds for the 5 different configurations tested.

No significant difference in the tensile strength of the cold weld was found between predominantly one-sided or two-sided flashing. Tensile tests on the strand without cold welds are included for comparison.

DISCUSSION—PART 1

No significant difference was found between cold welds with scissors- and pinch-cut end preparation. Five to 10 repetition welds have similar cross sections. Welds with less than 5 repetitions were much less reliable. Welds with more than 10 repetitions generated excessive flashing that interfered with the motion of the dies. The cold welds made with a 0.254-mm limit on the die travel (5PP) formed cold welds with flashing that was more difficult to remove. Longitudinal sections of cold welds from both scissors- and pinch-cut ends showed similar flow pattern morphology. Many samples show a flow pattern where all of the filaments from one strand go to one side of the flashing. This does not imply a poor quality weld. The cold welds made from incomplete travel of the cold weld dies (5PP) have a dead zone where the filaments have not been extruded out into the flashing. The lack of extrusion may result in poor bonding due to remaining oxide from the original strand end surface. This may explain the low tensile strength and large C of V in these welds. Perhaps the incomplete extrusion is one of the reasons for cold weld failure on the cabling line. A general precaution of slowly and completely executing each repetition of the cold weld is recommended.

Tensile data show that cold welds typically have about 75% of the tensile strength of the strand itself (625–650 MPa vs. 760–820 MPa). Scissors-cut strand ends tend to result in cold welds with slightly higher tensile strength. The 5PP samples had a lower tensile strength and a larger variation. The C of V for each type of end preparation and number of cold weld repetitions, with the exception of the 5PP samples, was similar (within 3%) to the C of V for the virgin strand. The tensile load on a strand during the cabling operation typically does not exceed 50 N, which results in a maximum stress level of 100 MPa. All of the cold welds fabricated had tensile strengths that greatly exceed 100 MPa. When care is taken to make complete motions of the cold weld dies (avoiding the partial motion as simulated in the 5PP samples), the tensile strength of the cold weld routinely exceed 600 MPa.

Table 1. Ultimate stress in MPa for different cold weld processes.

Test no.	No Cold Weld	5S	5P	5PP	10S	10P
1		688			651	609
2		640		360	637	646
3	768	639	624	244	667	604
4	767	615	644	531	619	585
5	822	675	647	320	665	617
6	817	676	646	306	657	637
7	829	705	654	548	682	625
8	831	678	649	419	637	675
9	813	641	645	545	656	627
ave.	807	662	644	409	652	625
std. dev.	27	29	9	120	19	26
C of V	0.034	0.044	0.014	0.294	0.029	0.042

EXPERIMENTAL—PART 2

Six batches of strand pieces from the ASST program were analyzed for the yields of cable without cold welds. The cold weld-free yields are compared for these batches with average PLs ranging from 1086 m to 7544 m. If breaks in strand processing are distributed randomly in a production unit, then the distribution of PLs is exponential. From an exponential distribution of the form $e^{-\alpha x}$, an expression for the distribution can be derived when adequate boundary conditions are known. In this study, the maximum PL was taken to be 100 kg, which was assumed to be a machine capacity limit for final size strand. The minimum practical PL was assumed to be 1 kg. The theoretical yield of cable from strand without cold welds can be calculated as a function of the median mass piece length (the piece length where half of the total delivered strand mass is longer and half is shorter).

RESULTS—PART 2

Six production batches of SSC conductor have been procured for ASST magnets. Three vendors, Intermagnetics General Corp. (IGC), Oxford Superconducting Technology (OST), and Supercon, Inc. (SCN) produced both Inner and Outer billets.[2] The number of billets in each Inner and Outer batch ranged from 3 to 5. In each batch, the number of full coil lengths obtainable was calculated along with the fractional coil length remainder. In this work, the required coil length was specified as 675 m for Inner cable and 900 m for Outer cable. The cable yield for no cold welds was calculated as the number of coil lengths of 675 m for Inner or 900 m for Outer obtainable divided by the total delivered length of conductor in the batch. Table 2 shows the average PL, the median mass piece length, and the cable yield without cold welds. In each case, additional coils can be made with cold welds distributed among several of the coils so as not to violate the cold weld spacing requirements in any one coil. The yield, therefore, in the maximum number of cold weld situations is estimated to be 98% and approximately independent of PL for PLs that exceed 3 coil lengths.

Table 2. Average and median mass piece length and theoretical cold weld-free cable yield from strand purchased by SSC.

Vendor	Cable Type	Avg. PL (m)	Median Mass PL (m)	Cold Weld Free Cable Yield (%)
OST	Inner	1086	1351	67.5
IGC	Inner	1587	2215	77.0
SCN	Inner	3225	4710	89.4
OST	Outer	1556	2300	69.4
IGC	Outer	3963	5805	89.5
SCN	Outer	7544	12033	94.3

The 100 kg maximum PL was converted to a value M of 26,000 m for Inner strand and 40,000 m for Outer strand. The minimum deliverable PL was taken to be 1 kg or approximately 300 m. Assuming that the finished strand has the form of an exponential distribution represented by $y = e^{-\alpha x}$, the median mass PL can be expressed by the ratio of integral equal to 0.5, as follows:

$$\frac{\int_{300}^{L} e^{-\alpha x}\,dx}{\int_{300}^{M} e^{-\alpha x}\,dx} = 0.5, \tag{1}$$

where L is the median mass piece length. The integral has a solution of the form $(e^{-\alpha x})/(-\alpha)$.

Eq. 1 can be solved by iteration for α when L is fixed and M is defined as above for Inner and Outer strand. The solution is:

$$e^{-\alpha L} = 0.5\left(e^{-\alpha M} + e^{-\alpha 300}\right). \tag{2}$$

Values of α were determined for L values of 1000, 1500, 3000, 6000, and 10,000 m for Inner and Outer strand. In addition, an L value of 15,000 m was used for Outer strand. Inner strands cannot have a median mass length L of 15,000 m in an exponential distribution with a maximum length of 26,000 m. Figure 5 contains a plot of the resulting equations for Inner strand.

The SSCL cable specifications imply a specific median mass PL. The specifications state that 85% of the total mass of a production unit must be in lengths greater than 1500 m. Setting up the integral as before:

$$\frac{\int_{1500}^{M} e^{-\alpha x}\,dx}{\int_{300}^{M} e^{-\alpha x}\,dx} = 0.85, \tag{3}$$

the solution is:

$$e^{-\alpha 1500} = 0.15\, e^{-\alpha M} + 0.85\, e^{-\alpha 300}, \tag{4}$$

where M is 26,000 m for Inner and 40,000 m for Outer. Eq. 4 can be solved for α through iteration. By comparing this α to the previous α values calculated above, minimum median mass piece lengths are approximately 5500 m for both Inner and Outer.

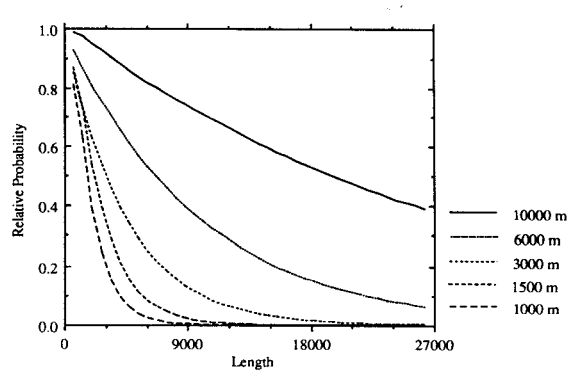

Figure 5. Relative PL probability curves for Inner strand as a function of median mass PL.

From these curves, the theoretical yield of cold weld-free strand can be determined. The area under a region of the curve, divided by the total area under the curve, represents the fraction of the conductor having the PL defined by that region. For example, Inner strand lengths between 675 m and 1350 m yield 675 m of useful material; lengths between 1350 m and 2025 m yield 1350 m of useful material, and so on. The calculated yield of Inner and Outer strand in cable as a function of the median mass piece length is shown in Figure 6. The data from Table 2 are included as discrete data points; they demonstrate very good agreement with the actual batches of production material.

DISCUSSION—PART 2

The exponential distribution model for the production strand PLs is validated by the close agreement to the batches of SSC conductor with median mass piece lengths from 1500 m to 12,000 m. The model is helpful for determining the impact of using cold welds in cable when a cable vendor's median mass strand PL is known.

The current SSC specification implies a median mass piece length of 5500 m . This represents a cold weld-free yield of 88% for Outer and 92% for Inner cable. If SSCL's experienced coil failure rate of 6% due to cold welds is typical, then it is clear that cold welds are not practical for median mass piece lengths greater than approximately 6800 m for Inner and 10,500 m for Outer strand. These lengths exceed the minimum target levels in SSCL specifications; however the cable vendors should be strongly aware of the advantages of long PL from the perspectives of reducing strand production cost and increasing cable yield.

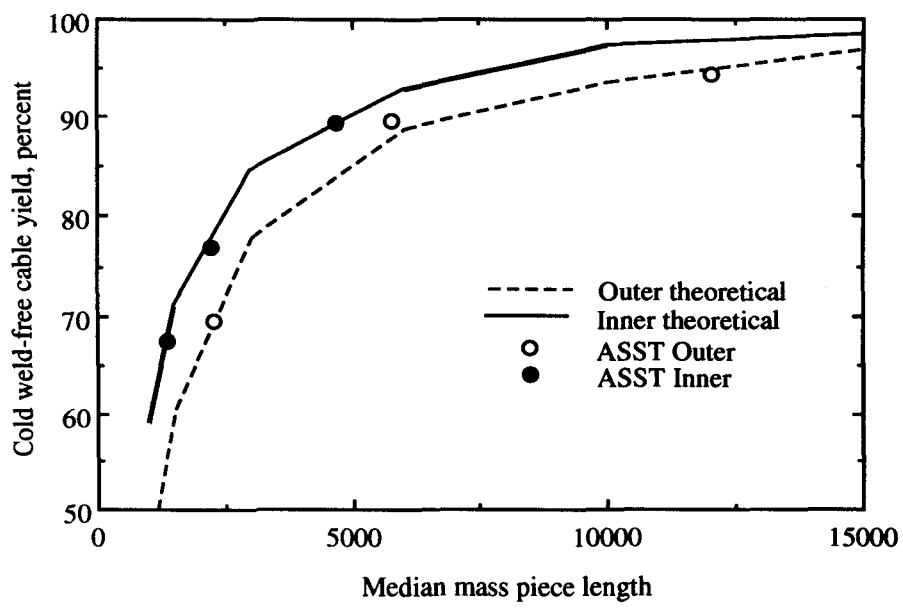

Figure 6. Theoretical cold weld-free yield of cable from strand as a function of median mass piece length. Calculations of theoretical yield from ASST material from Table 2 are included as discrete points.

ACKNOWLEDGEMENTS

The authors thank D. Washburn and V. Levy for technical assistance in this work. The SSC Laboratory is operated by the Universities Research Association, Inc., for the U. S. Department of Energy under Contract number DE-AC35-89ER40486.

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