SSCL-470

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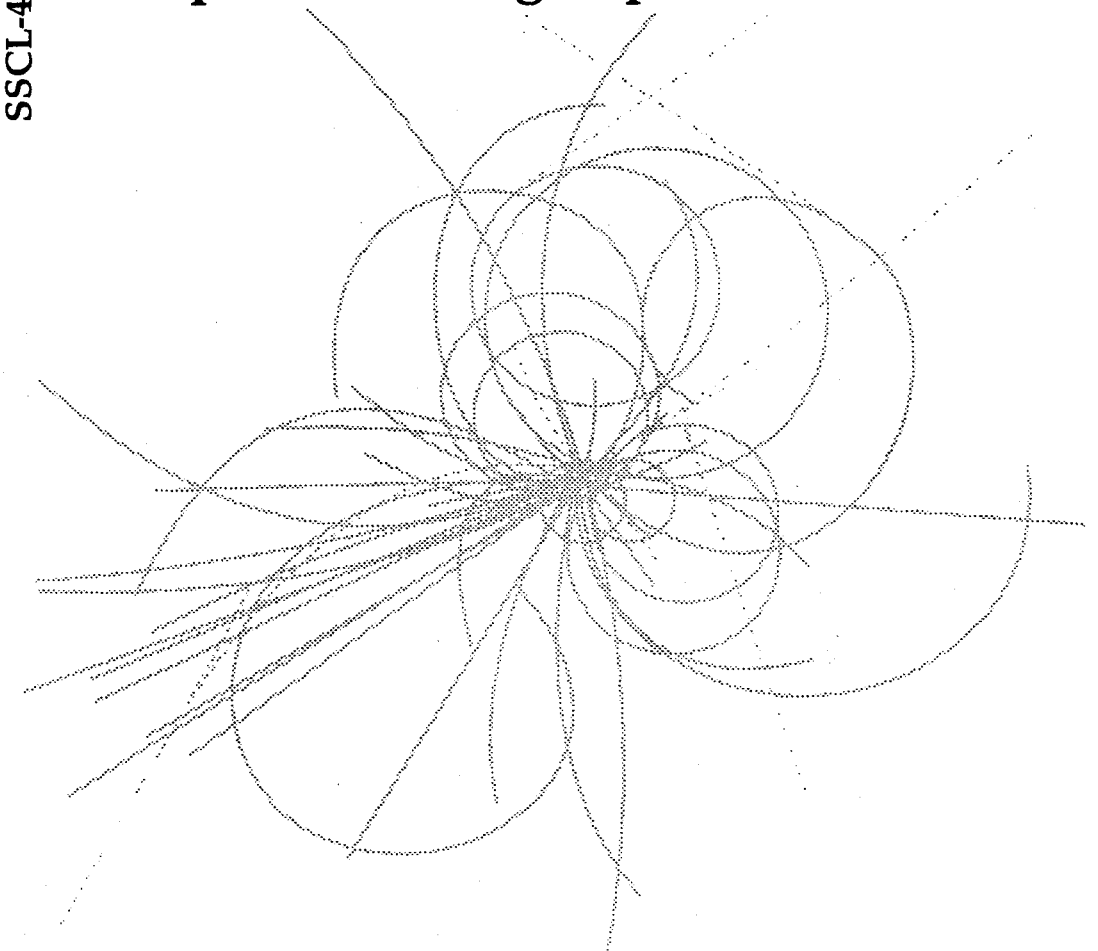
Superconducting Super Collider Laboratory



Quality Analysis of Superconducting Wire and Cable for SSC Dipole Magnets

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QUALITY ANALYSIS OF SUPERCONDUCTING WIRE AND CABLE FOR SSC DIPOLE MAGNETS:
A comparison of recent performance and specification requirements*

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A comparison of recent performance and specification requirements.

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Abstract

A critical component of the SSC collider dipole magnets is superconducting cable. The uniformity and reliability requirements for the dipoles place stringent demands on the cable. These needs have been defined as various contract requirements in the material specifications for NbTi alloy, superconducting wire and cable. A supplier qualification program is being started by the SSCL with industry to establish reliable sources of superconductor cable. Key to this qualification program is the establishment by industry of detailed process methods and controls for wire and cable manufacture. To monitor conductor performance, a computer database is being developed by the SSCL Magnet Systems Division Quality Assurance Department. The database is part of a program for insuring superconductor uniformity by focusing on the understanding and control of variation. A statistical and graphical summary of current data for key performance variables will be presented in light of the specification requirement for uniformity. Superconductor material characteristics to be addressed will include: Wire Critical Current (I_c), Copper-to-Non-Copper Ratio (Cu:SC), Wire Diameter, Wire Piece Length, and Cable Dimensional Control.

Introduction

As previously reported [1] the SSCL QA organization has been developing Quality Assurance requirements for superconductor which are now included in the material specifications. Part of these quality requirements are a set of data reports for source material data, manufacturing process data, and product performance data. It is our belief that source material variation and manufacturing process variation contribute to final product performance variation. With the wealth of data to be generated by the production of SSC cable, we hope to identify significant relationships between the observed sources of variation. When the required data is received by the SSCL, it will be stored in a computer database and used by the QA department to try to understand and thereby limit performance variability.

An initial question to be studied with the data will be the degree to which present specification tolerances and statistical process capabilities are compatible. Related to the question of tolerances and capabilities is the question of whether or not statistical thinking can be applied to the measurement and control of *performance variables* such as I_c and Cu:SC Ratio, as well as directly controllable variables like Strand Diameter and Cable Mid-Thickness. Preliminary analysis of available superconductor material data will be presented in this paper for key specification variables. This work is an example of the kind of analysis which will be applied to this and other data to be supplied under the supplier qualification contracts. Results of analysis performed to date on the limited data set indicates the present process is marginally "statistically" capable. Considerable improvement seems possible if efforts are taken to apply established statistical methods to the production process.

The source for the information presented in this paper is superconductor data provided by the supplier for wire delivered during the past year. This conductor is planned for use in 50 mm Collider Dipole Magnets (CDM). The superconductor was ordered and produced to meet the minimum requirements of specification SSC-MAG-M-4141, for the 40 mm CDM program and later transferred when the program changed in early 1990. Due to space limitations for this publication, the discussion of I_c and Cu:SC will be limited to Outer wire only.

Wire Critical Current and Cu:SC Ratio

CDM Outer Wire (1.8:1)

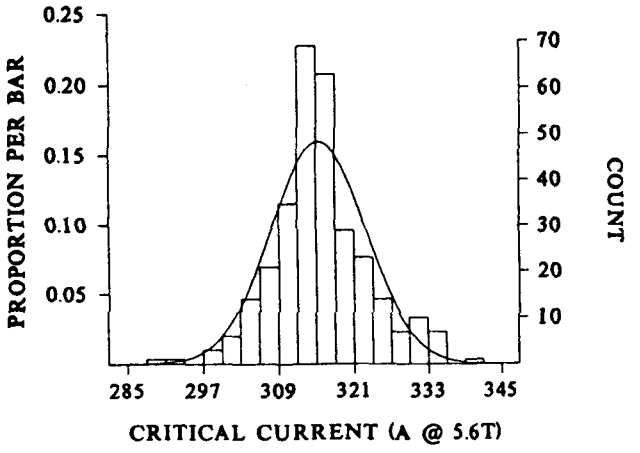
Table 1 is a summary of data from eight Type-1.8 Outer billets having a recieved yield of 2,969,959 ft. (905.5 km) in 304 pieces. Each piece was tested as part of the producer's final verification. A survey of several test laboratories performed by SSCL QA during 1990 has confirmed measurement uncertainty for "accuracy" (between test sites) in the range of ± 5 %, plus additional uncertainty due to "repeatability" and "reproducibility" (within test site) [2]. The Outer I_c data presented in this paper has not be adjusted for "accuracy" uncertainty, since only one producer supplied the information. The I_c specification minimum is 285 A @ 5.6T, the Cu:SC specification is 1.8 ± 0.1:1.

Table 1: CDM Outer Wire I_c and Cu:SC Performance

Average I_c : 315.4 (A @ 5.6T)
I_c Standard Deviation (σ): 7.5 A
I_c ± 3 σ range: 337.958 - 292.805 = 45.15 A
I_c Percent Coefficient of Variation (%C.V.): 2.38%
Average Cu:SC: 1.78:1
Cu:SC Standard Deviation: 0.037
Cu:SC ± 3 σ Range: 1.89 - 1.67 = 0.22

Figure 1 is a frequency histogram of the Outer Wire Ic, smoothed with a normal density function based on the mean and standard deviation of the Ic data. Figure 2 is a similar graph of the Cu:SC data.

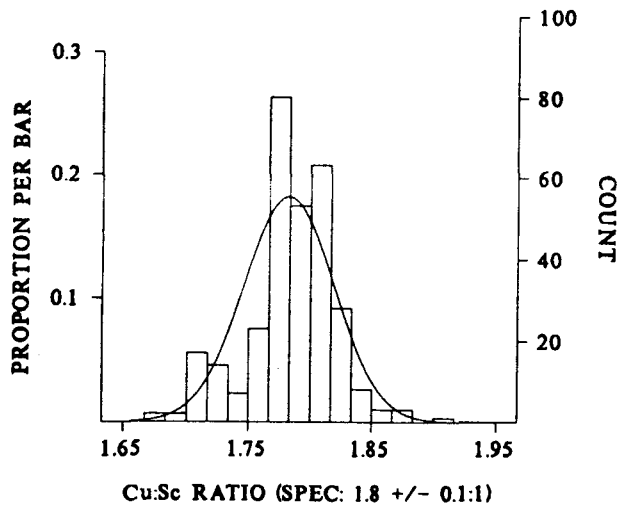
(Figure 1)
CDM OUTER WIRE Ic DISTRIBUTION



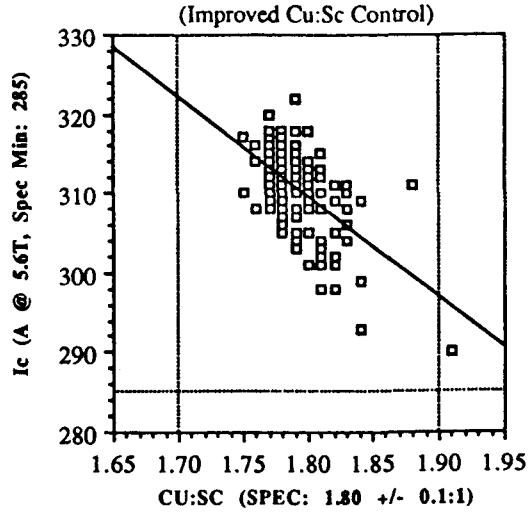
Process Capability

One of the objectives of the SSC QA monitoring effort will be to determine not only if the conductor manufacturing process is producing wire and cable within the specification tolerance limits but also if it is consistent and in *statistical control*. By one definition, a process is described as being in statistical control when a stable system of *chance causes* seems to be operating.[3] The key to this definition is stability of natural (or chance) variation. Statistical methods have been available for many years which provide quantitative means for determining when observed change is natural

(Figure 2)
CDM OUTER WIRE Cu:SC DISTRIBUTION



(Figure 3)
SSC Outer Strand Ic vs Cu:Sc
(Improved Cu:Sc Control)



(due to chance causes) or unnatural (due to *assignable causes*).[4] An initial step in applying statistical thinking to a manufacturing process, is to determine the level of constant cause or natural variation in the process, by collecting data from the process according to a specific statistical model and then comparing the process variation (± 3 σ range) to the specification tolerances. An index of process capability has been defined which compares observed process variation and specification tolerances. Cp (process capability) = (Tolerance Range) / (Process 6σ), where σ is the estimated standard deviation of the process variable being evaluated. This definition assumes the variation being measured is "normal" or gaussian.

For a given normally distributed process variable centered on the specification tolerance nominal, and having a Cp of 1.0 or better, one may infer that the process ± 3 σ range falls within the tolerance range. A goal of SSCL QA for the superconductor process is to work to establish a Cp ≥ 1.3, meaning that the process ± 4 σ range (or better) would fall within the tolerance range. This allows some room for process drift around the specification nominal without the loss of "control". Once the process capability has been determined, additional steps can be taken to establish control limits for acceptable variation. These limits will serve to indicate the introduction of "assignable cause" variation, or the presence of conditions signifying a change from the expected state of stability.

Cu:SC Ratio Process Capability

Based on the eight Outer billets evaluated, the process capability for the supplier's Outer Cu:SC is Cp = (.20/.22) = 0.91. This result means the specification tolerance will be difficult for the supplier to achieve on a consistent basis for all pieces and in fact on some occasions out-of-tolerance material may result. From a "quality" perspective such performance suggests the need for either process improvement or a re-consideration of specification tolerance limits.

Independent of SSCL QA efforts, the superconductor supplier for the Outer wire discussed above has been working to improve the manufacturing process and has achieved some success with Cu:SC control. The data from five recent Outer billets shows a Cu:SC Cp of 1.5, the process ± 4.5 σ range falls within the tolerance range. This result is displayed in figure 3 as wire I_c vs. Cu:SC per measured sample.

The five billets, in 145 pieces, have an average Cu:SC of 1.79 and a Cu:SC ± 3 σ Range of 1.72 - 1.86:1. Interestingly, the improvement in Cu:SC variation control appears to have also had a beneficial affect on I_c variation. The average I_c is 310.6 A and the Ic % C.V. is 1.67%. The measured I_c variation is roughly 20% less than that measured in the three billets produced before the improvements were introduced. If such control is consistently maintained, the need for cable strand mapping by critical current may become unnecessary.

Wire Diameter

Outer Wire Diameter Tolerances and Process Capability

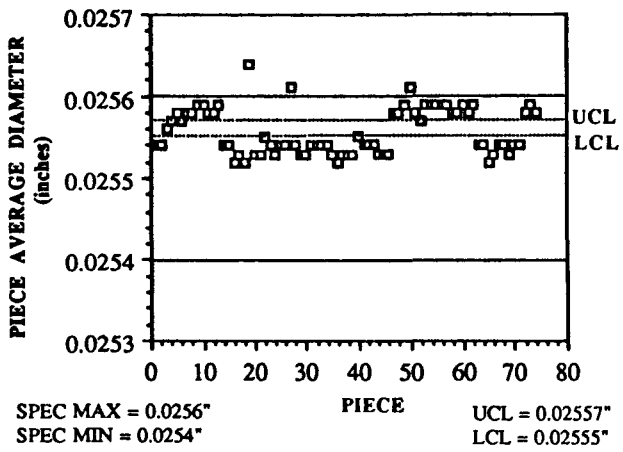
Evaluation of two billets from which continuous laser micrometer statistical distribution data is available indicates a Cp = 1.33. Table 2 is a summary of the data based on the piece average and standard deviation for each delivered length of wire. The wire was produced to a diameter tolerance of 0.0255" ± 0.0001".

Table 2: Outer Wire Diameter Performance:
(2 Billets, 74 pieces)

Quantity (ft): 747,213 (227.8 km)
Average Length: 10,097 (3,078 m)
Piece Average Diameter (in): 0.02556 (0.649 mm)
Piece Average Std. Dev. (in): 0.000025 (0.0006 mm)
Wire Diameter ± 3 σ Range: 0.000150 (0.0038 mm)
Wire Diameter Process Capability (Cp): 1.33

Figure 4 displays the piece distribution data for the two billets where each box represents a single piece average (XBAR).

(Figure 4)
STRAND DIAMETER VARIATION
(with XBAR SIGMA control limits)



The upper and lower control limits (UCL, LCL) in the graph above were computed based on a statistical model which uses the average standard deviation (SBAR) for the measured subgroups.[5] In this case SBAR is the average of the individual piece standard deviations. By observation there appear to be two distributions, one above and the other below the computed control limits. This suggests the data represents two source "populations", (possibly two different wire drawing dies were used, or some other systematic effect was at work). Had the process been controlled to produce superconductor closer to the specification nominal, most likely none of the pieces would have exceeded the specification tolerance (0.0256") , and the combined total size variation for the two billets may have been reduced. This example demonstrates the importance of consistently working to achieve the process specification "nominal".

Wire Piece Length

Wire Piece Length Distribution

Experience to date indicates that the typical wire piece length distribution is "exponential", not normal. By definition, the exponential distribution describes "the interval of *time* or *space* it takes to get a 'success' " from a particular *time-based* or *event-based* probability experiment or trial. Examples of observed exponential distributions include: Inter-arrival times to service centers (i.e. Toll Booths, Restaurants), or the distance to the next defect in a length of fabric. [6] An interesting property of exponential distributions is that the average and standard deviation are equivalent. Relative to the SSC specification, the exponential characteristic of piece length implies that a certain number of breaks seem to be unavoidable, and that from a standard unit of material (billet) one may expect more *short* pieces than *long*. Minimizing the number of pieces (wire breaks) per billet is the challenge.

Piece Length Results Compared to Specification Requirements

Table 3 is a summary of piece length data for the Outer billets in the study. Note that the average and standard deviation are nearly equivalent.

Table 3: Wire Piece Length Summary

	Outer (1.8:1)
Billets	8
Pieces	304
Sum (ft./km)	2,969,959 (905)
Piece Average (ft./km)	9,770 (3.0)
Standard Deviation (ft./km)	10,740 (3.3)
Average Billet Yield	71.95 %
(100% = 516,000 ft / billet) [7]	

Table 4 describes the billet yield and the percent of "short" piece (<5,500 ft.) yield greater than the specification allowed maximum of 15%. In this case the "expected yield" used for the calculation is simply the "average yield" of the delivered wire. [8]

Table 4: Wire Piece Length Performance to Specification

	Billet	--------- Short Piece Summary ---------		
Billet	Yield %	Σ (<5.5K ft.)	% of Yield	< 15% ?
1	64.7	164,842	44.4	no
2	74.1	23,102	6.2	yes
3	72.0	73,956	19.9	no
4	72.1	16,457	4.4	yes
5	71.9	84,901	22.9	no
6	77.1	35,518	9.6	yes
7	76.2	6,518	1.8	yes
8	67.4	0	0	yes

Frequency of wire breaks is viewed as one indicator of *conductor quality*. The number of pieces or breaks in a given billet implies the presence of break inducing conditions. For each break that occurs, a certain (unknown) number of unbroken "weak spots", proportional to the number of pieces, are believed to exist. Recent experience with wire breaks during respooling (without die reduction) and cabling (prior to the turkshead) from billets with poor piece length distributions gives support to this theory. The use of eddy current examination and defect analysis may be able to confirm these ideas.

Wire Piece Length Process Capability

From these results one can see that work is needed to improve average piece length. As of this writing, there is insufficient data to be able to determine with certainty if all suppliers have different or similar piece length capabilities, though there have been some isolated examples of much better average piece length performance than described above. Also we have not been able to determine if NbTi alloy or it's "source" has any significant effect on the observed behavior. Based on the results described, achieving the piece length specification remains a challenge.

Cable Dimensional Control

Outer Cable Dimensional Tolerances and Performance

A recent tooling change (turkshead roll set) on one of the cable machines used to produce Outer cable introduced a significant increase in thickness variation. Analysis of the event has lead to the application of a process capability study and the establishment of "real time" Statistical Process Control limits for SSC cable produced by the SSCL. Table 5 is a summary of the specification dimensional requirements for 50 mm CDM Outer Cable, (note: the use of "English" units is due to the current CMM convention.):

Table 5: 50 mm CDM Cable Dimensional Requirements

Mid-Thickness: 0.04550" ± 0.00025" (1.156 ± 0.006 mm,)
Width: 0.4598" + 0.002 / - 0.000 (11.68 + 0.05 - 0.00 mm)
Keystone: 1.01 degree ± 0.1 degree

Table 6 summarizes thickness results for the first ten lengths of 50 mm CDM cable. Note, these cables were processed without the application of on-line statistical methods.

Table 6: Cable Mid-Thickness Performance (without SPC)

Cable:	Average Thickness:	± 3 σ Range:	Cp:	Data Points:	Length (ft.):
1	0.04547"	0.00048"	1.04	208	1969
2	0.04550"	0.00018"	2.78	196	1969
3	0.04553"	0.00030"	1.67	554	5520
4	0.04548"	0.00048"	1.04	146	1320
5	0.04546"	0.00042"	1.19	145	1160
6	0.04546"	0.00042"	1.19	68	660
7	0.04562"	0.00024"	2.08	67	645
8	0.04553"	0.00078"	0.64	162	1381
9	0.04553"	0.00060"	0.83	613	5568
10	0.04552"	0.00084"	0.60	575	5510

During post-process off-line evaluation of cable data, the effect of the turkshead tooling change was first observed as an alarming increase in the thickness variation (± 3 σ Range), even though the average thickness continued to be very near nominal.

Outer Cable Process Capability Analysis

The following method was applied to evaluate the change in process variation. As a result, the process was brought back to a state of stability:

1.) Identify and correct "assignable cause" for dramatic change in process variability, (cause: tooling "run out", correction: re-grind rolls with bearings under a simulated load).
2.) Perform Process Capability Analysis (data collection and evaluation), to determine the sensitivity of the process to the tolerance requirements, (is Cp > 1, can process ± 3 σ "fit" inside specification tolerance?).
3.) Calculate preliminary statistical control limits from process capability data.

4.) Apply preliminary statistical control limits, to achieve on-line "real time" control of variation with process targeted on specification nominal.
5.) Observe process to identify additional sources of "assignable cause" variation, (i.e. turkshead control).
6.) Adjust subgroup XBar (average) and Range control limits based on experience, to improve process stability.

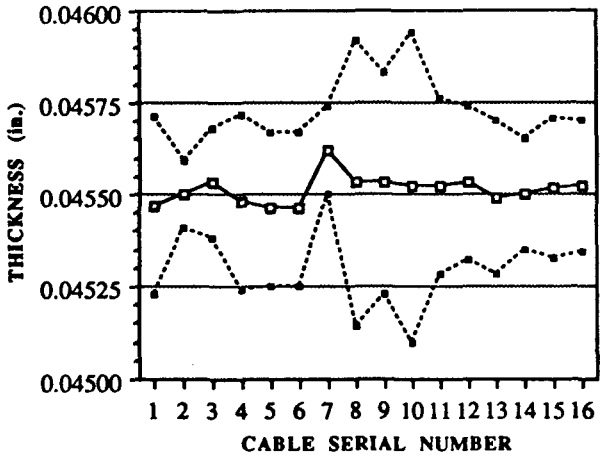
Results of the analysis of the cable machine and actions taken reveal a return to relative process stability as described in Table 7.

Table 7: Cable Mid-Thickness Performance (with SPC)

Cable:	Average Thickness:	± 3 σ Range:	Cp:	Data Points:	Length (ft):	Action:
11	0.04552"	0.00048"	1.04	1469	4393	Grind rolls
12	0.04553"	0.00042"	1.19	255	1235	
13	0.04549"	0.00042"	1.19	854	4211	
14	0.04550"	0.00030"	1.67	1107	5538	Grind rolls
15	0.04552"	0.00038"	1.30	233	1142	
16	0.04552"	0.00036"	1.39	879	4375	

The thickness data for all 16 cables is summarized in figure 5, showing average thickness and ± 3 σ range:

(Figure 5)
CDM OUTER CABLE MID-THICKNESS
CMM SUMMARY
(Average, +/- 3 Sigma)



Additional cable improvement is now being investigated through a study of turkshead adjustment control. According to the available process data, a Cp of better than 1.9 is possible on this machine, if the ability to make fine adjustments to thickness in the range of 0.000025" can be developed. This cable thickness example has demonstrated the value of statistical methods to identify, reduce, and control process variation.

Conclusion

Analysis has shown that the superconductor process is statistically capable (i.e. Cp > 1.0, ± 3 σ) of meeting or exceeding most of the present specification tolerances that have been evaluated. Achieving a routine capability Cp ≥ 1.3, (± 4 σ) centered on a specification nominal should become an industry goal for future effort in this area. Once confidence has been gained in applying statistical thinking to the superconductor manufacturing process, achievable control limits can be applied to the manufacturers process specification as well as the SSCL performance specification. Learning how to monitor and respond to process variability in these and other areas throughout the manufacturing process will be a significant challenge for industry as it works on the SSCL superconductor supplier qualification program over the next two years.

Acknowledgement

I wish to recognize the recent efforts of several colleagues, in evaluating and improving cable dimension control: Mike Boivin (New England Electric Wire Company), Denis Christopherson, Mark Erdmann, Dan Fielding, Scott Graham, and Roy Hannaford (all of the SSCL).

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