SSCL-361

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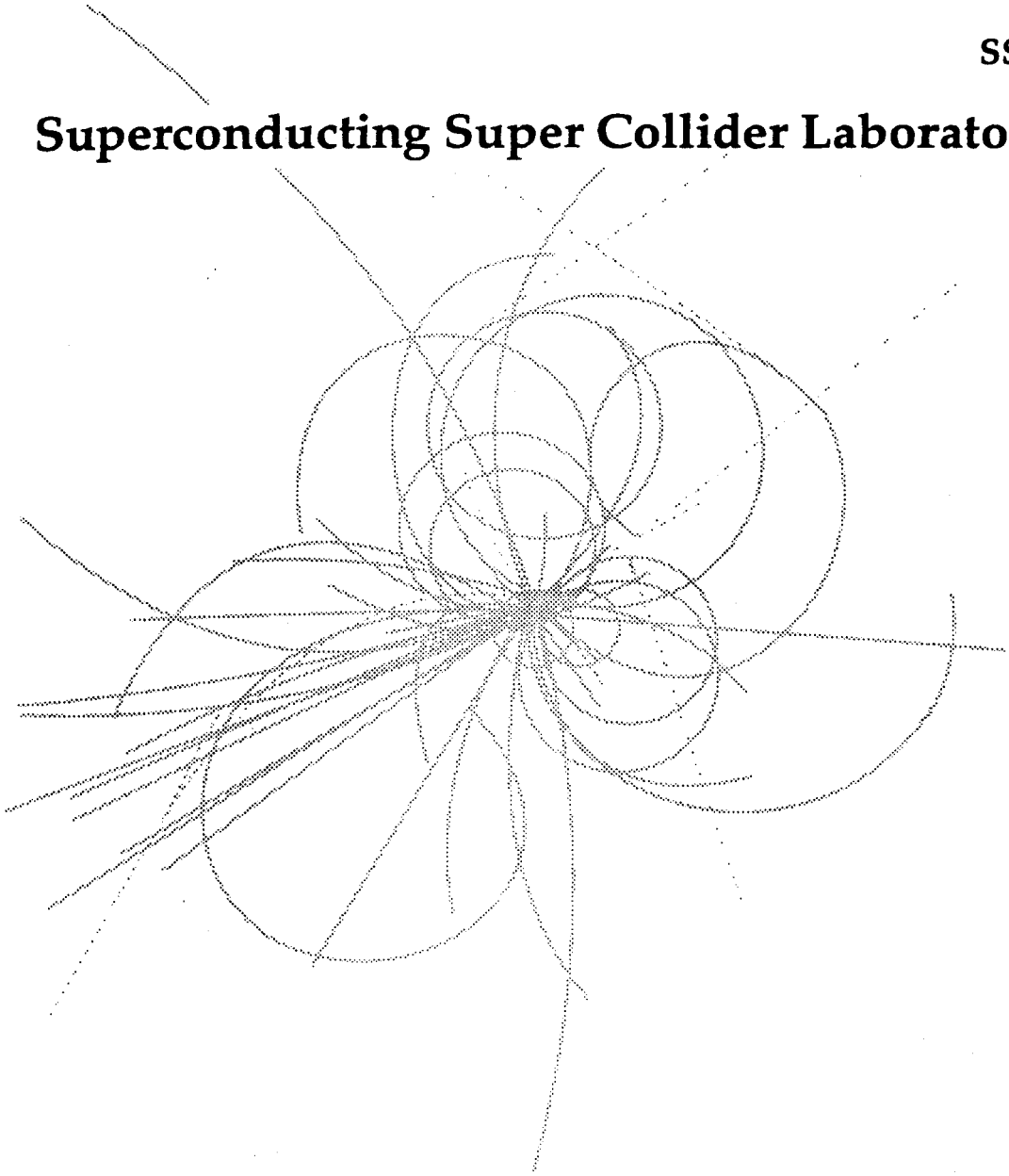
Superconducting Super Collider Laboratory



The Quality Assurance of Superconducting Wire and Cable for SSC Magnets

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THE QUALITY ASSURANCE OF SUPERCONDUCTING WIRE AND CABLE FOR SSC MAGNETS

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ABSTRACT

The success of the SSC depends on the consistency and uniformity of the superconducting magnets used in the main collider rings and the high energy booster. To a great extent the success of the magnets depends upon the quality of the superconductor wire and cable used in coil windings. As the SSC project has begun its transition from Research to Development, a new laboratory organization has been established to carry the design requirements from concept to reality. The SSCL Magnet Systems Division Quality Assurance Group has been working on the development of a quality management and analysis system for insuring superconductor uniformity through the understanding and control of manufacturing variation. Key areas of the QA activity include: 1.) the design and development of a computer database and analysis system for the collection and statistical analysis of superconductor materials data (containing: source physical and chemical properties, billet process history, and final product performance data); and 2.) the development of wire and cable product specifications which focus on the control of variation. As a result of this work several new concepts have been developed which will affect the traditional approach to superconductor wire and cable production.

INTRODUCTION

The main purpose of this paper is to describe the present state of planning for the management of superconductor material quality, as viewed by the SSCL Magnet Systems Quality Assurance organization. Since all of the material produced to date for the SSC has been made under R&D (rather than Production) contracts, many of the quality management ideas presented here have yet to be adopted by industry. The initiation this spring of the two year Conductor Qualification Program [1] with industry, containing up to 280 billets in seven contracts, provides a vehicle for the introduction and preliminary verification of these plans. Future technical and management reviews will confirm the soundness of these ideas. The major focus of this paper will be the "means to achieving quality" which are currently within the direct scope of SSCL QA activity; (in particular, portions of the Magnet Components Database along with the Material Specification requirements).

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract. No. DE-AC02-89ER40486.

SUPERCONDUCTOR MATERIALS REQUIREMENTS FOR COLLIDER DIPOLES

In order to measure the relative magnitude of the task facing the SSCL and the superconducting materials industry, a summary of the conductor requirements for Collider Dipole cable is presented.

	INNER CABLE		OUTER CABLE	
Strand Number:	30		36	
Strand Diameter:	0.808 mm	(0.0318")	0.648 mm	(0.02551")
Cable Length:	19,973,904 m	(12,408 mi)	13,946,524 m	(8,664 mi)
Cable Mass:	1,256,104 kg	(1,385 Tons)	1,331,746 kg	(1,468 Tons)
Billets:	3,641		3,805	

The cable quantities listed are based on absolute magnet requirements, and have no allowance for yield losses [2]. For representative purposes a "billet" of multifilament conductor is 305 mm diameter prior to extrusion and yields approximately 350 kg of bare cable. Actual billet dimensions may vary according to supplier process requirements.

In the past year less than twenty billets of dipole conductor have been produced for the SSCL by industry. Starting in 1994 the annual production rate will need to be approximately one thousand billets per year each, for Collider Dipole inner and outer conductor.

QUALITY ASSURANCE GOALS FOR COLLIDER CONDUCTOR

The following are the primary goals of the QA program for superconductor materials [3,4].

A. Conductor Defect Prevention.

B. Conductor Defect Detection.

C. Reduction and Control of Manufacturing Process Variability.

D. Overall uniformity of magnet coil performance.

The program being designed to meet these goals is intended to be practical not legalistic. If successful, the result of this effort will be to eliminate much of the mystique surrounding the production of superconductor materials. Simply stated, a major objective of this plan is to reduce or eliminate the possibility of a supplier "losing the superconductor recipe" for unidentifiable reasons, once it has been established.

THE MEANS TO ACHIEVING QA GOALS

Achieving quality is not something that will just happen because someone somewhere has written a specification or invoked a mil standard. As in any worthy endeavor, quality will be the result of careful planning and hard work. We believe the key to meeting the stated goals are "attention to detail" and "communication" at all levels of the program. This means paying the price in effort to predict, plan, and document the inputs necessary for a stable manufacturing process, followed by observation and evaluation of the feedback coming from the process. The following outline describes the fundamental steps or "means" to achieving quality upon which the SSCL QA Plan is based. In terms of the philosophy described above, these steps may be viewed as indicating a relative order of significance.

The Means to Achieving QA Goals:

A. Close SSCL interaction with superconductor suppliers.

B. Supplier establishment of a well characterized "baseline" process containing clearly defined and measurable controls throughout the process.

C. Continuous monitoring and analysis of product performance and process variation by the Supplier and the SSCL.

D. SSCL QA-1: Seller Quality Assurance Requirements, (Quality Management System requirements, appended to product specifications).

E. The Wire and Cable Specifications.

To the extent that producers typically look upon the specifications as an "end" in themselves, the ordered outline above indicates a need for adjustment in such thinking. The formal specifications are a starting point for communicating fundamental requirements. As both the SSCL and Industry learn more about the process, product specification requirements may be more sharply focused to satisfy overall program goals. Successful cable performance in the collider ring is the "end".

THE MAGNET COMPONENTS DATABASE

To implement the monitoring and analysis elements of the plan, a computer database has been designed and installed at the SSCL [5,6]. The database will be used for storing important information regarding all materials used in the collider magnets. The database is known as MAGCOM. The MAGCOM system, a network accessible computer database, resides on a Sun 4 Computer running the UNIX operating system. The actual database is built on SYBASE, a SQL relational database application. For superconductor materials, the database has been organized to contain information about: source material physical and chemical properties, manufacturing process history, manufacturing process variation data, and final product performance. The database is not all inclusive, it contains only the minimum information which the SSCL considers critical to maintaining component uniformity and traceability.

To simplify setting up a link with industry, an IBM PC version of the conductor database has been developed [7,8]. The definition of data requirements for the system has been appended to the wire and cable specifications [9] in the form of manual data sheets, (see Table 1 below). During the start up phases of the Conductor Qualification Program, procedures for computerized data management and transfer will be worked out between the SSCL and each contracted supplier.

Monitoring Conductor Process Stability

From a QA perspective, this database will be essential for establishing confidence in the stability of the suppliers' process. We will use the information collected to monitor the magnitude of manufacturing variation and try to correlate particular process conditions (dependant variables) to conductor performance requirements (response variables) [10]. We will also try to answer the following general questions by evaluating the data.

A. How do supplier controllable process parameters effect final product performance?

B. Are supplier established manufacturing tolerances and SSCL specification requirements sufficient to assure uniformity and consistency in the final cable?

C. Can statistically significant shifts be detected and corrected before performance is adversely affected?

Monitoring Source Material Consistency

Source material data (NbTi, Nb, Cu), will be used to provide traceability from the cable back through the process to the raw material. We will also monitor material variability from lot to lot. As above, we hope to answer some fundamental questions with the data.

A. To what extent does measurable variation of the physical and chemical properties (within the established tolerance limits) relate to final product performance?

B. As with the conductor process, can significant material performance shifts be detected and corrected before they become problems?

C. Are SSCL tolerances sufficient to assure uniformity and consistency in the final cable?

DATABASE CONTENT

The minimum data collection requirements for conductor have been appended to the material specifications for NbTi, Nb, Wire and Cable, as summarized below.

TABLE 1: DATABASE CONTENT

DOCUMENT	DATA SHEET	REQUIRED INFORMATION
M50-000003	COPPER MATERIAL SOURCE DATA.....	LOT CHEMICAL ANALYSIS
M50-000004	NbTi ALLOY INGOT CHEMICAL ANALYSIS DATA...	INGOT / MELT CHEMICAL ANALYSIS
M50-000005	NbTi ALLOY LOT CERTIFICATION DATA.....	LOT CHEMICAL ANALYSIS
M50-000006	NIOBIUM SHEET CHEMICAL/MECHANICAL DATA..	LOT CHEMICAL & MECHANICAL ANALYSIS
M50-000007	MONOFILAMENT BILLET PRODUCTION DATA.....	BILLET ASSEMBLY DATE SOURCE MATERIAL
M50-000008	MULTIFILAMENT BILLET PRODUCTION DATA.....	BILLET ASSEMBLY DATE SOURCE MATERIAL
M50-000009	BILLET WELD / COMPACTION DATA.....	WELD & COMPACTION DATES, WELD INSPECTION & COMPACTION EFFECT PRESSURE / TIME / TEMP
M50-000010	BILLET EXTRUSTION DATA.....	DATE / VENDOR / SEQUENCE PRE-HEAT INFORMATION EXTRUSION RUN FORCE BILLET TEMPERATURES
M50-000011	MULTIFILAMENT STRAND HEAT TREAT HISTORY.	IDENTITY / QUANTITY FURNACE INFORMATION DATES IN & OUT VISUAL CONDITION TIMES / TEMPERATURES

TABLE 1: (continued)

DOCUMENT	DATA SHEET	REQUIRED INFORMATION
M50-000012	STRAND CHEMICAL / MECHANICAL / ELECTRICAL TEST DATA	PRESENCE OF TWIST CU:SC RATIO SPRING BACK SHARP BEND TEST FIELD (TESLA) DIAMETER CRITICAL CURRENT, I_c QUALITY INDEX, "n" RESISTANCE R295 K RESISTANCE R10 K
M50-000013	STRAND PRODUCTION DATA	FINAL ANNEAL STATE PIECE LENGTH PIECE WEIGHT DIAMETER STATISTICS
M50-000014	CABLE RUN DATA	GENERAL INFORMATION MID-THICKNESS WIDTH KEYSTONE ANGLE
M50-000015	CABLE STRAND-MAP DATA	MATERIAL IDENTITY / LOCATION / WELDS / I_c
M50-000016	CABLE EXTRACTED STRAND CRITICAL CURRENT TEST DATA	TEST FIELD (TESLA) STRAND I_c QUALITY INDEX "n" CU:SC RATIO STRAND AVERAGE I_c CABLE EST. I_c

CURRENT FUNCTIONAL STATUS OF THE QA DATABASE

The IBM/PC conductor database presently in use in the SSCL QA Group has been developed on Ashton/Tate dBASE III PLUS Version 1.1. The data flow diagram (Table 2) outlines the present functional activities associated with superconductor data management.

PERFORMANCE DATA

Conductor performance data is being manually provided by the suppliers and SSCL Conductor Engineering. The data is currently limited to the following items:

WIRE DATA

A. Wire Identity
B. Critical Current
C. Cu:SC Ratio
D. Strand Diameter
E. Piece Length
F. Sharp Bend and Spring Back, (periodically)

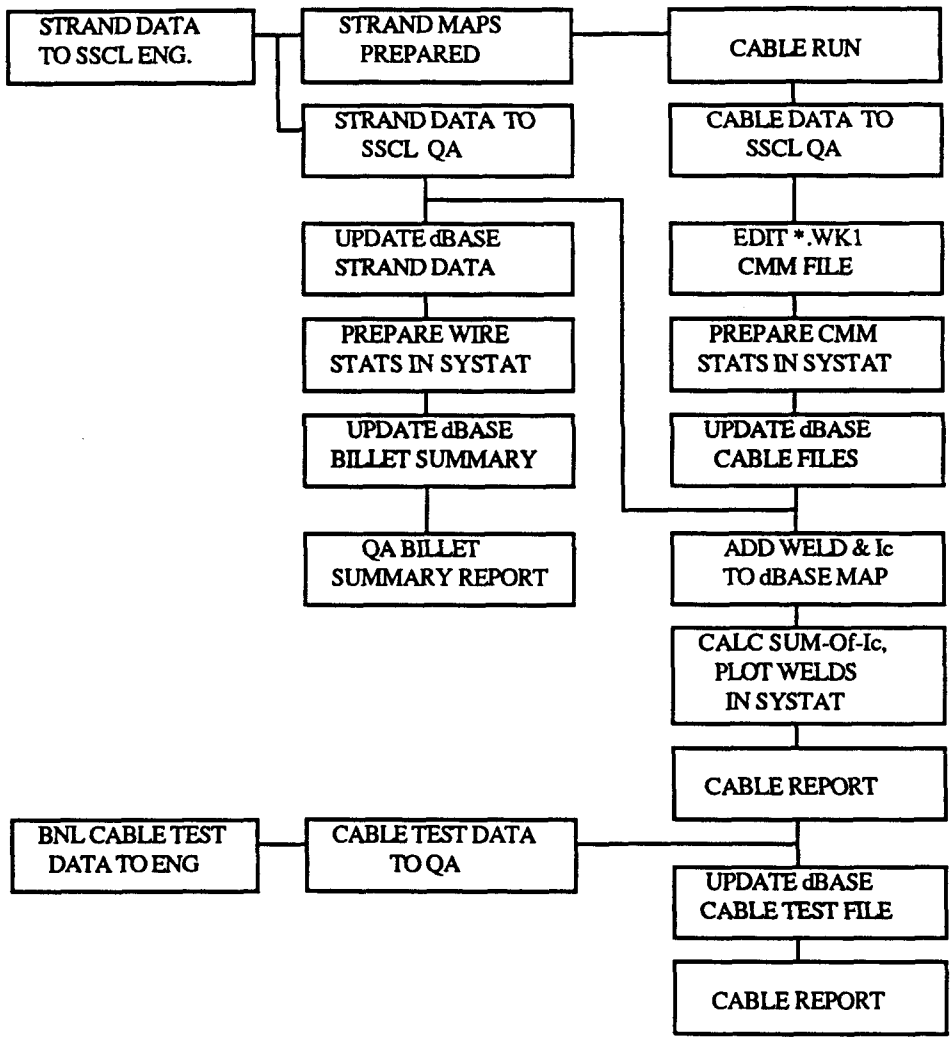
CABLE DATA

G. Cable Strand Map
H. Cable Measuring Machine Data
I. Cable Run Report
J. Cable Test Data (from BNL)

SOURCE MATERIAL AND MANUFACTURING PROCESS DATA

No source material or manufacturing process data is being submitted by industry at this time. This is one of the major areas of the QA program in which the SSCL is breaking new ground with industry. It is expected that during the next year this link will be firmly established.

TABLE 2: DATA FLOW DIAGRAM

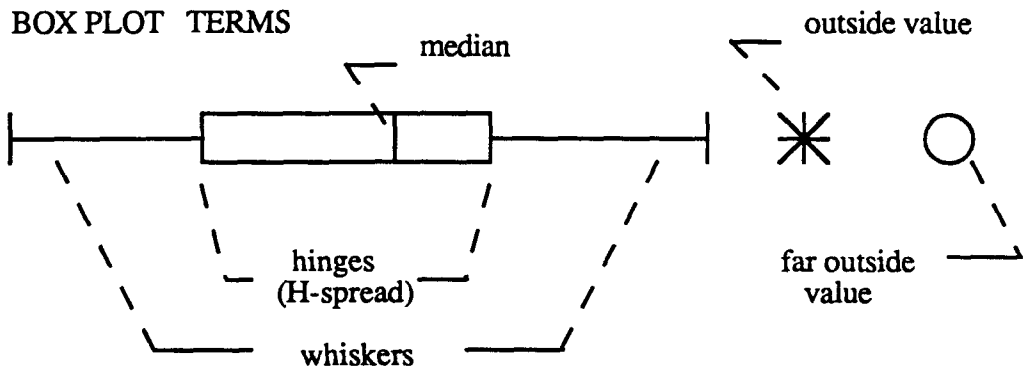


DATA ANALYSIS

Data analysis is performed with SYSTAT version 5.0 [11] a command language statistical analysis application available for IBM/DOS, Apple/Macintosh, DEC/VAX and UNIX operating systems. The goal of the QA Group is to establish "automated" routines to perform primary data reduction tasks. At this time conductor performance data is transferred to SYSTAT format for statistical analysis and graphing through the use of commands as desired. Statistics for cumulative billet pieces are used as input for a billet summary/history dBase file. Periodically, reports of conductor performance are prepared for management using these tools [12]. One of many types of data manipulation available with SYSTAT is shown below, Chart-1: Box Plot: Outer Billet I_c (@ 5.6T). Before considering the graph, a brief explanation of box plots is provided.

Box plots are a tool for exploratory data analysis. They provide a means of represent data distribution values graphically, but without showing each and every point. A box plot provides a "picture" of the middle of a data set, roughly how spread out the middle is, and how the tails (or extreme values) relate to the middle. With one look the viewer can easily form impressions of overall level, amount of spread, and symmetry in the data. What makes them particularly useful is that with SYSTAT an entire data set (for example: I_c by billet)

containing hundreds of individual observations can be summarized with one simple command. In other words box plots provide a "quick and dirty" way of getting meaningful information out of a lot of data [13]. The specific elements of a box plot as implemented in SYSTAT are described below [14].



MEDIAN The middle value of an ordered set of observations. The median splits the data set in half.

HINGE The middle value of an ordered half from the data set.

EXTREME VALUES (Outliers)

Outliers are values so low or high they seem to stand apart from the rest of the data set. When calculating simple statistics, such as the mean and standard deviation, outliers can have an unrealistic or exaggerated effect on the results. Extreme values may or may not be "real" however they should be investigated. In box plots two terms are used to denote outliers, "outside" values and "far outside" values.

Outside values are defined by "inner fences", and plotted as asterisks.

Inner Fences: lower hinge - (1.5 x H-spread) upper hinge + (1.5 x H-spread)

Far Outside values are defined by "outer fences", and marked with empty circles.

Outer Fences: lower hinge - (3 x H-spread) upper hinge + (3 x H-spread).

BOX The box is simply a drawing defined by the hinges (hinge spread).

WISKER A line which approximately denotes the range (min to max) of the data. Specifically, wiskers extend to the outermost data value on each end that is still not beyond the corresponding inner fence. In SYSTAT the whiskers show the range of values which fall within 1.5 H-spreads of the hinges. They do not necessarily extend to the inner fences.

EXAMPLE FROM THE SSCL CONDUCTOR DATABASE

Outer strand I_c for wire delivered in 1990 will be described in Charts 1, 2 and 3. Chart-1: Box Plot displays individual billet I_c distribution for 8 billets (a total of 304 wire sample measurements). Added to the display are ± 3 sigma limits, based on the data set average and sample standard deviation. As a comparison the same data is displayed as a typical Frequency Histogram, in Chart-2. Summary statistics for I_c and Cu:Sc Ratio are provided as well.

OUTER BILLET I_c

CHART 1: **Box Plot**

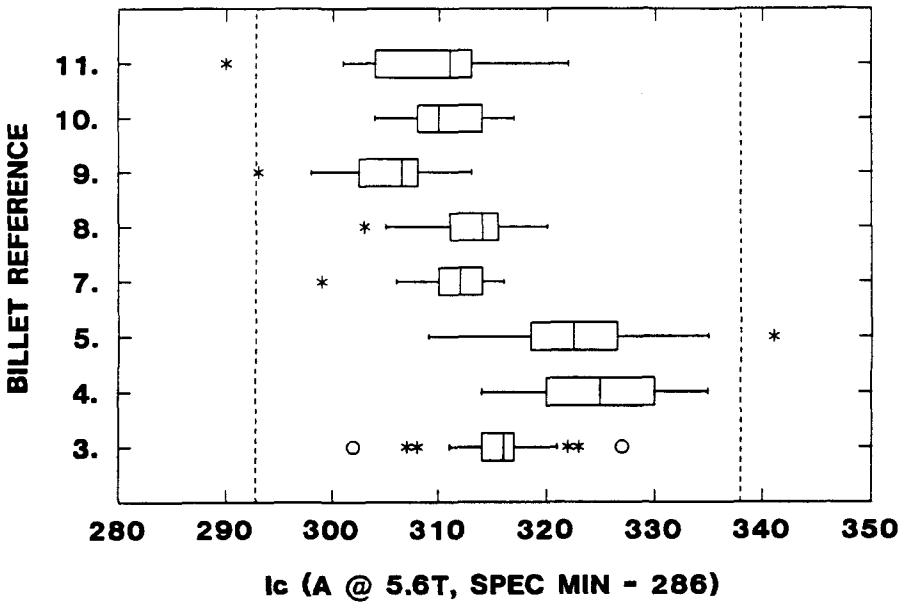
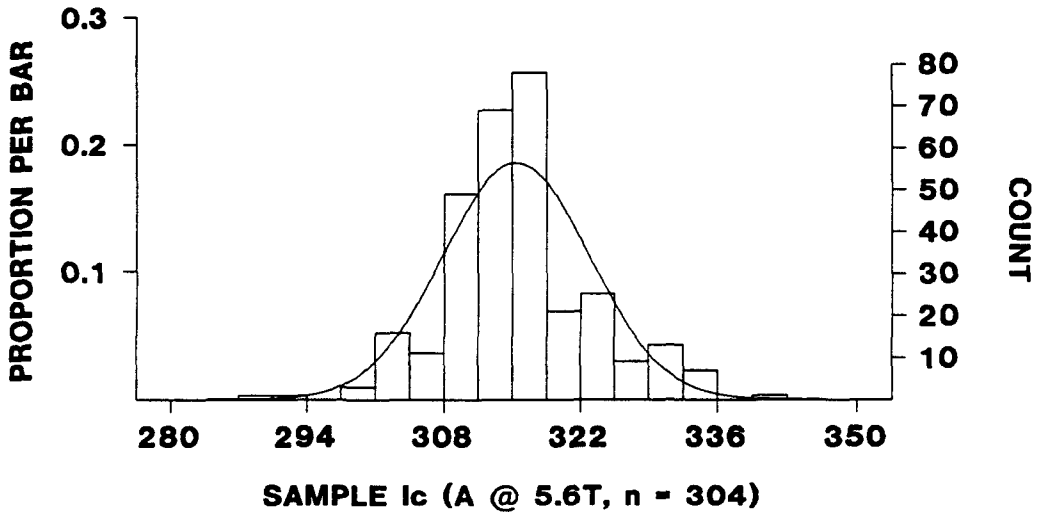


CHART 2: **Frequency Histogram**

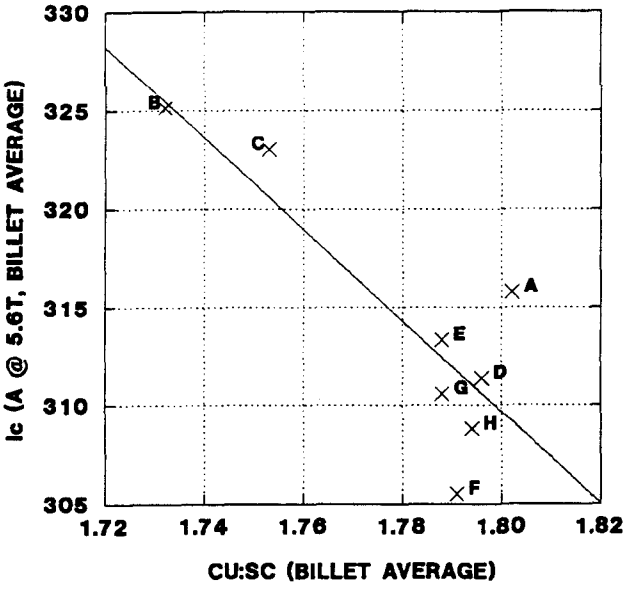


BILLET NUMBER:	≤ 5		≥ 7		COMBINED	
	I_c	Cu:Sc	I_c	Cu:Sc	I_c	Cu:Sc
MEASUREMENTS	160	160	144	144	304	304
MEAN	319.66	1.77	310.63	1.79	315.38	1.78
STANDARD DEV	6.69	0.04	5.21	0.02	7.53	0.04
%C.V.	2.09	2.51	1.68	1.24	2.39	2.06

(%C.V. = [(1 Sigma / Mean) * 100])

Billet Numbers ≤ 5 and ≥ 7 are from different production lots. All were produced by one supplier. With the box plot one can see billets 4 and 5 stand out from the others, both in average I_c and in the magnitude of I_c spread. This difference is closely related to Cu:Sc ratio, as shown in Chart-3. To the degree that strand Cu:Sc variation along the length of a billet is both "real" and "controllable", uniformity of conductor performance will be affected.

CHART 3: **Outer Billet I_C & Cu:Sc Variation**



Note: The letter labels above, correspond to the billet reference numbers in chart 1, (i.e. A = 3).

CABLE MEASURING MACHINE DATA

A CMM Data disk with LOTUS .WK1 file of required data is being provided by SSCL Engineering after each cable run. The Lotus file is manually edited for use in SYSTAT. Summary reports and graphs are generated from the CMM data, (for individual cables as well as groups of cables, by measured attribute). Much of this work is handled in QA by two programmed menu systems for 50mm and 40mm CDM Cable. Chart-4 is a summary of cable mid-thickness for 8 pieces of 50mm CDM cable totalling 4,458m (14,624 feet). The chart shows the cable mid-thickness average and ± 3 sigma range. Tolerance limits are placed at 0.0457" and 0.0453".

CHART 4: **50mm CDM Outer Cable Mid-Thickness**

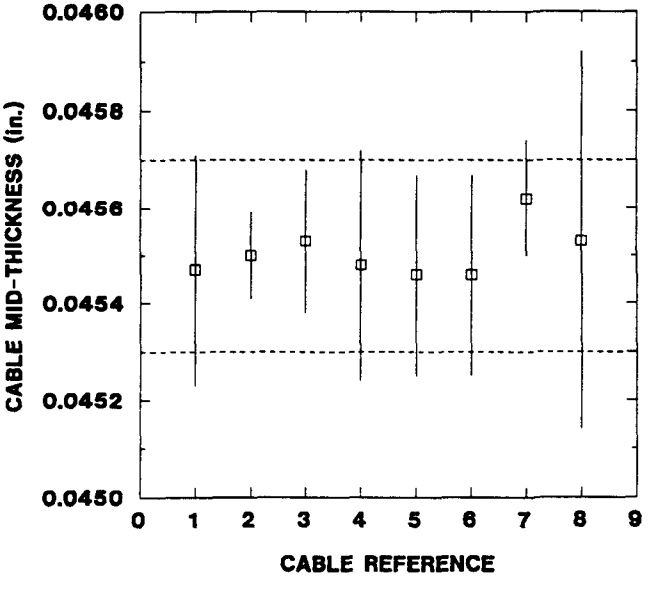


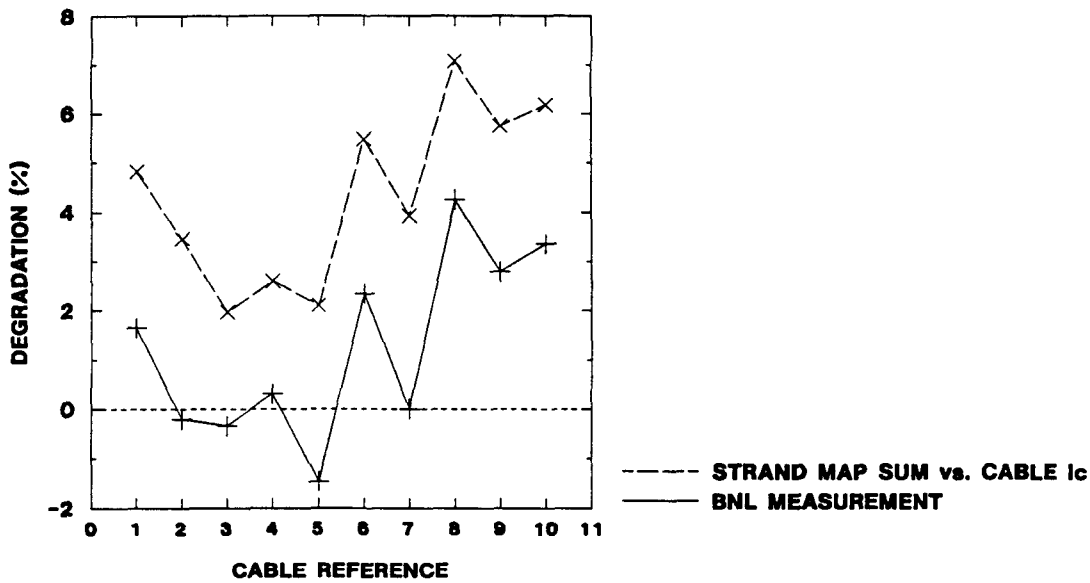
Chart-4 above shows cabling is being controlled such that the average thickness is generally near the nominal. However, thickness variation within these cables, as described by the ± 3 sigma range, is generally consuming the allowable specification range. The cable specification is not currently being interpreted "statistically". Presently, cable acceptance is based on CMM results within the tolerance limits. The CMM is programmed to need to see 3 data points out-of-spec before alarming. Analysis of the implications of these difference is needed.

Additional cable run data sheets, including strand maps, are received from Engineering with the CMM disk. This data is still being manually entered into the QA database.

CABLE ELECTRICAL TEST DATA

Cable test data is currently being provide by BNL [15] through Engineering on a periodic basis, (BNL measures "full" cable performance). Once received at the SSCL, this data is being stored in a QA dbase file which relates the cable test results to the original cable strand map I_c data, Another example of process monitoring capability is shown in Chart-5: Strand Map To Cable Degradation. The chart shows I_c degradation for recent 40mm and 50mm CDM cable, as calculated from BNL measurements and also as compared to the Sum-of-Strand I_c from strand map data. The difference between the two is believed to be due to the relative "accuracy" of the measurement sources (BNL and the wire supplier), as discussed in a separate IISSC paper [16].

CHART 5: **STRAND MAP TO CABLE I_c DEGRADATION (OUTER)**



NOTE: Cable Reference Numbers above do not match those shown in chart 3.

The current cable specifications provide for the qualification of "extracted strand" measurements for cable verification by the supplier during the Conductor Qualification program.

MAGNET PRODUCTION DATA

Magnet Production Data beyond cabling is not being processed as part of the QA database at this time. Work in this area is being organized by the Magnet Systems Test and Data Management Section and by the several sites for magnet production (FNAL, BNL, LBL, KEK, SSCL MDL, Saclay, and Industry). However, in order for magnet producers and users to gain maximum benefit from the conductor data, work needs to be done to match actual

cable usage during coil winding to the source cable strand map. Additionally, a reference table matching magnet, coil, and cable identities needs to be established and maintained.

dBASE TO SYBASE TRANSFER

The current method of transfer is to give the Test and Data Management Group a data disk with the appropriate QA dbase files. The data is converted directly to SYBASE form for use in the publicly available database MAGCOM. This happens about once a month or as requested. Direct electronic transfer is now possible, all we need to do is establish the desired procedure.

MATERIAL SPECIFICATION QA REQUIREMENTS

The current SSCL CDM Conductor Specifications are listed in the references [9]. The following are the "Quality" specific requirements from the wire and cable specifications. Items marked with a "*" in the left margin indicate requirements, topics, or levels of activity which are "new" to the superconductor materials industry. Many of these ideas have been developed in consultation with others in the national laboratory community [17,18].

A. Traceability to source materials:
   (a.) Wire: Mono-Billet, NbTi, Nb, Cu.
* (b.) Cable: Multi-Billet, "Production Unit", Billet "Segment".
* B. Process History by billet "Production Unit".
* C. SSCL "Change Control" over Manufacturing Plan.
* D. SSCL "Change Control" over Manufacturing Machines and Methods.
* E. Application of Statistical Process Control, (SPC).
F. Control of Non-Conforming Material.
* G. Cable "I_C Strand Mapping", for Sum-of-Strand I_C Variation Control.

The following are highlights of the key Quality Management Requirements from SSCL-QA-1:

A. Establishment of an effective supplier QA program.
B. Development of written detailed process procedures.
C. Establishment of cleanliness control procedures.
D. Use of a supplier program for subcontract control.
E. Measuring and test equipment calibration.
F. SSCL source inspection/surveillance of the conductor supplier and his subcontractors as necessary.

Test and Inspection of wire and cable

* A. Physical & Chemical Properties of source materials.
B. Mechanical & Electrical Properties.
* C. Sampling Levels for tests, during Phase I of the Qualification Program.

CONCLUSION

The past year of SSCL operations has provided a unique opportunity to prepare a comprehensive "Quality Plan" as well as data collection and analysis tools for SSC superconductor materials. Of invaluable significance has been the opportunity to integrate these plans and ideas as part of the Engineering Specifications for wire and cable. The establishment of close ties between Engineering. Test & Data Management, and Quality at the early stages of planning for the SSC is key to our ultimate success. In the year ahead, we look forward to completing the building of a strong foundation for the future, with the addition of Industry participants.

Acknowledgement:

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy, under Contract No. DE-AC02-89ER40486.

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   NbTi Wire (Inner), SSC-Mag-M-4145; NbTi Wire (Outer), SSC-Mag-M-4146;
   NbTi Cable (Inner), SSC-Mag-M-4147; NbTi Cable (Outer), SSC-Mag-M-4148,
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