Relativistic Heavy Ion Collider
Magnet Division Procedure

Proc. No.: RHIC-MAG-M-8002

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Class: Ancillary Specification
Title: Nb-Ti Superconductor Wire for RHIC Helical Dipole Magnets

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REVISION RECORD

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1. Scope:

This specification establishes the requirements for the manufacture, inspection, test, identification and delivery of Nb-Ti superconductor wire for use in RHIC Helical Dipole magnets.

The main emphasis of the specification is on adherence to a uniform production method for the conductor rather than on peak performance. The goal is to have the magnetic field behavior of all magnets in the RHIC accelerator be identical and, because of the effects of conductor magnetization and its possible time dependence, it is imperative that conductor be fabricated using materials with the same specifications and processes with the same steps, parameters and tolerances. Therefore, the procurement will be from one vendor with strict adherence to that vendor's process; no process changes will be permitted.

2. Applicable Documents:

The following documents in effect on the date of invitation to quote form a part of this specification to the extent specified herein. Unless otherwise specified, the issue date or revision level shall be that in effect on the date of invitation to quote.

- ASTM F68 — Standard Specification for Oxygen-Free Copper inWrought Forms for Electron Devices - for classification requirements (Plate 1).
- ASTM B170 — Standard Specification for Oxygen-Free Electrolytic Copper-Refinery Shapes - chemistry requirements governed by B170, Grade 1.
- RHIC-MAG-M-4000 — Niobium-Titanium Alloy Bars and Rods
- RHIC-MAG-M-4001 — Barrier Grade Niobium Sheet
- BNL-QA-101 — Brookhaven National Laboratory Seller Quality Assurance Requirements
- MIL-I-45208 — Inspection System Requirements
- RHIC-MAG-M-4135 — RHIC Superconductor Wire Twist Measurement
- BNL Dwg. 12000028 — Wire, Conductor, Helical dipole

3. Requirements:

3.1 Raw Material: Raw material used in the manufacture of RHIC Nb-Ti composite wire shall be procured to the requirements of this specification and inspected/tested by the vendor for conformance to those requirements before release for production use.

3.1.1 Nonconforming Raw Material: Material found to deviate from requirements shall not be dispositioned through any seller review process without prior specific written approval from BNL.

3.1.2 Raw Material Identification: Each lot of wire raw material shall be uniquely identified to allow all vendor manufacturing, test, and inspection records for finished wire to be traceable to the original lot of raw material.

3.2 Technical Properties

3.2.1 Conductor Type: The conductor shall be a composite of Nb-Ti filaments in an oxygen-free copper matrix.

3.2.2 Conductor Billet Components: The components described below shall be used to fabricate the superconductor.

3.2.2.1 Niobium-Titanium Alloy: The alloy composition shall be Nb 47 ± 1 weight percent Ti, and shall be high homogeneity grade or BNL-approved equivalent. This tolerance on Ti content covers all Nb-Ti bars to be used to fill the order. It must be purchased by the vendor in one uniform lot to meet the requirements of the specification RHIC-MAG-M-4000.

3.2.2.2 Copper: With the exception of the billet end caps, all copper raw material purchased by the vendor to be used for billet fabrication shall meet the chemistry requirements of ASTM B170 - Grade 1, and have residual resistance ratio (RRR) greater than 250:1. This copper, when finally used for the billet cans, shall be wrought, not cast, and shall meet the classification requirements of ASTM F68, Class 2 or better. The copper used for the billet end caps shall be wrought, not cast.

3.2.2.3 Niobium Material for Diffusion Barrier Construction: Niobium must be purchased by the vendor to meet the requirements of the specification RHIC-MAG-M-4001.

3.2.3 Conductor Fabrication: The procedures listed below must be followed during billet assembly or processing.

3.2.3.1 Monofilament Shape: The monofilament rods used to assemble the multifilament billet shall have hexagonal cross section.

3.2.3.2 Diffusion Barrier Construction: A niobium diffusion barrier shall be placed between the Nb-Ti and the copper in the monofilament billet. Its thickness and quality shall be sufficient to prevent formation of copper-titanium compounds during wire fabrication.

3.2.3.3 Filament Array: The design of the overall placement of filaments inside the billet shall be submitted to BNL for approval with the bid package. There shall be a copper island in the center of the billet; it shall comprise a minimum of 10% of the total area of the final wire.

3.2.3.4 State of Wire Anneal: In order to facilitate the use of the wire for coil winding, the wire is to be received in a ductile condition. Annealing must be done in a continuous-feed furnace to avoid wire sticking and associated deformation. Specific technical requirements are given by Wire Springback Test and Wire Minimum RRR given in Tables I and II, respectively.

3.2.3.5 Production With No Deviations: The specification for Nb-Ti, copper and Nb materials used for wire manufacturing shall be the same throughout the production. Also, the production steps, parameters and tolerances for the wire fabrication shall remain the same.

3.2.3.6 Production Unit: All superconductor wire produced to this specification shall be processed in "production units".

A "production unit" consists of material from a common multifilament billet which undergoes identical mechanical and thermal processing, and shall be identified as such. A "production unit" may be less than one full billet. All material from a "production unit" shall be thermally cycled together in the same furnace, for each and every heat-treatment.

Work-In-Process material from a "production unit" shall remain physically grouped together throughout all phases of the manufacturing process. Any portion of a billet which becomes separated from its "production unit" shall be considered non-conforming and shall be addressed as such.

3.2.3.7 Control of Manufacturing Machines and Methods: The machines and equipment used to process all superconductor made to this specification shall be identified for BNL and documented as part of the vendor's Quality Plan. No changes to machines, methods or processes shall be permitted without prior written approval of BNL.

3.2.3.8 Wire Eddy Current Testing: All wire is to be eddy current tested at final size over the entire length of each spool. All records of tests shall be maintained carefully by the vendor for audit by BNL. A calibration method must be developed by the vendor and agreed-upon by BNL to assure the necessary sensitivity and reproducibility of the eddy current test method.

3.2.3.9 Frequency of Sample Testing: The expected frequency of wire testing by the vendor is summarized in Appendix A. The transmittal of the data and samples to BNL is given in paragraphs 4.2, 4.4 and 4.5.

3.2.3.10 Manufacturing Data: BNL does not require regular transmittal of manufacturing data related to wire fabrication. These data will be audited regularly by BNL staff at the vendor facility. The vendor must maintain manufacturing data records for two (2) years after the date of acceptance of the wire by BNL.

3.2.4 Wire Performance Requirements: The superconductor wire must meet the performance requirements described in Tables I and II and explained in subsequent paragraphs. Checks of the wire dimensional, mechanical and electrical requirements are the responsibility of the vendor. A 10 ft. long wire test specimen, which is adjacent to the location used for each vendor wire electrical test, shall be delivered to BNL; see paragraph 4.5, and note that samples from every wire spool must be sent to BNL. The frequency of wire sample testing is given in Appendix A.

Table I. Wire Dimensional and Mechanical Requirements

| Requirement | Value | Defined in Para. No. |
|---|---|---|
| Nominal Filament Diameter | 10µm | 3.2.4.1 |
| Nominal Filament Spacing | >1µm | 3.2.4.1 |
| Copper-to-Non-Copper Ratio | (2.5 ± 0.1):1 | 3.2.4.2 |
| Number of Filaments | 310±5 | 3.2.4.3 |
| Wire Diameter | 0.0130±0.0001 in. | 3.2.4.4 |
| Wire Twist Direction | Right | 3.2.4.5 |
| Wire Twist Pitch | 2.0±0.2 twists/in. | 3.2.4.5 & RHIC-MAG-M-4135 |
| Wire Sharp Bend Test | No Damage | 3.2.4.6 & Test Method 8002-1, App. B |
| Wire Springback Test | <1600 degrees (horiz.)<br><1750 degrees (vert.) | 3.2.4.7 & Test Method 8002-2, App. B |
| Wire Surface Condition | No defects | 3.2.4.8 |
| Wire Minimum Length | 10,000 ft. | 3.2.4.9 |

Table II. Wire Electrical Requirements

| Requirement | Value | Defined in Para. No. |
|---|---|---|
| Wire Minimum Critical Current at 5.0T | 66A | 3.2.4.10, 3.2.4.11 |
| Variation of Measured Wire Critical Current at 5.0T | ± 6A maximum limit | 3.2.4.10, 3.2.4.12 |
| Wire Maximum R(295) | 0.280 ohms/m | 3.2.4.14 and Test Method 4005-3, App. B |
| Wire Minimum RRR | 90 | 3.2.4.14 and Test Method 4005-3, App. B |

3.2.4.1 Nominal Filament Diameter and Spacing: The nominal filament diameter and spacing shall be defined by the billet design. Before fabrication, the vendor shall submit to BNL for written approval a drawing showing the billet assembly and dimensions to demonstrate that the nominal filament diameter and spacing shall be obtained at the final wire size. Shaving of the external copper during billet processing must be considered in the demonstration.

3.2.4.2 Copper-to-Non-Copper Ratio: The value of the ratio of copper volume to non-copper volume is to be 2.5:1. However, to simplify measurement there is no technical requirement for this parameter. Instead there will be a technical requirement for R(295), for RRR and for the wire diameter. The calculated copper-to-non-copper ratio will be greater than 2.4:1 provided that the wire diameter is within the specified tolerance, R(295) is less than a maximum and RRR is greater than a minimum value. See Appendix B for a description of this method.

3.2.4.3 Number of Filaments: The number of filaments for the RHIC production shall be within the value specified in Table I. This number shall remain fixed throughout the production within the specified tolerance.

3.2.4.4 Wire Diameter: The tolerance on the wire diameter is a maximum limit and does not include averaging or statistical weighing. The tolerance must be held for the wire measured across any diameter/axis. Verification of this diameter shall be determined by the vendor using an appropriately calibrated dual-axis laser micrometer used to check all of the wire produced after all fabrication steps are complete. The laser micrometer should be capable of detecting local variations in the wire diameter over a length of one-inch. Statistical analysis of laser micrometer measurements shall be provided by the vendor to BNL.

3.2.4.5 Wire Twist Direction and Pitch: All wire shall be right-twist so the filaments follow the same rotation as a right-hand screw thread. The wire is to be twisted before the final sizing die.Requirements on twisting shall apply over the full length of the delivered wire. No leaders with variable twist are allowed. The method to be used for wire twist measurement is given in RHIC-MAG-M-4135. The equipment is the responsibility of the vendor.

3.2.4.6 Wire Sharp Bend Test: The superconductor wire shall meet the sharp bend test requirements with no visible damage to the copper or to the filaments after etching. The test procedure is described in Appendix B.

3.2.4.7 Wire Springback Test: The superconductor wire shall meet the requirements of a springback test following the test procedure described in Appendix B, with the fixture mounted on a horizontal surface. If the fixture is mounted on a vertical surface, with wire and weight hanging freely, the maximum acceptable value shall be as given in Table I. The weight used for the corrector wire springback measurements is $(1.5 \pm 0.1)$ lb.

3.2.4.8 Wire Surface Condition: The wire surface shall be free of oil residue, all surface defects, slivers, folds, laminations, dirt, or inclusions. No filaments shall be visible. These conditions must be met for any sample of the wire inspected using a magnification of 10x. In addition, the wire is to be eddy current tested at final size over the entire length of each spool (see para. 3.2.3.8).

3.2.4.9 Wire Minimum Length: A minimum length requirement is imposed to assure high quality of the wire and its fabrication process, as well as to facilitate use of the wire during insulating and coil winding. Length shall be determined after all lead and end defects have been removed by cropping. These defects include areas of distorted cross section due to wire pointing by swaging, foreign material attached as a temporary leader, or areas of distorted filaments that occur at the start and end of an extrusion. A continuous compilation of wire lengths must be made by the vendor and provided to BNL.

3.2.4.10 Wire Critical Current Determination: The critical current values refer to a test temperature of 4.22K and a critical current criterion of $\rho = 1x10^{-14}$ ohm · m, based on the wire cross section area and with the applied magnetic field (given in Table II) perpendicular to the wire axis. The tolerance on the magnetic field is ± 0.01T in order that no field correction be necessary. Otherwise, the deviation from reference must be corrected. The field correction procedure must be approved by BNL. The maximum allowable departure from an angle of $90^0$ between the sample coil axis and applied field directions is 4 degrees ($\cos 4^0 = 0.998$). Larger angles must be approved by BNL in order to establish suitable treatment of data. No correction is made for self-field effects. Measurements at temperatures which differ from 4.22K by more than 0.02K must be corrected. A temperature correction procedure is suggested in Appendix B, Test Method 4005-3, para. A6. The critical current test procedure given in Appendix B is to be used. Although it is not included as a technical requirement, the Quality Index (n) is to be reported by the vendor with every critical current measurement. This parameter is described in Appendix B. It is required that under the test conditions the quench current, $I_Q$, be greater than the critical current. $I_Q$ is also to be reported by the vendor.

3.2.4.11 Wire Minimum Critical Current at 5.0T: The wire minimum critical current in Table II and the conditions defined in paragraph 3.2.4.10 correspond to a current density in the non-copper region of the wire of 2775 A/mm$^2$ at 5.0T, 4.22K, a nominal copper-to-non-copper ratio of 2.6:1, and a wire diameter of 0.0130 inches. No correction is made for self-field effects. If this minimum critical current will adversely affect the wire ductility, this should be brought to the attention of BNL. Also, see paragraphs 3.2.4.7 and 5.4.

3.2.4.12 Variation of Measured Wire Critical Current at 5.0T: The variation of the measured wire critical current at 5.0T shall remain within the given maximum limit from the running average throughout the entire production of each phase. Any wire with critical current outside this range will be rejected.

3.2.4.13 Wire Maximum R(295) and Minimum RRR: The resistance of the wire at room temperature [(295.0 ± 0.2)K] is frequently referred to as the normal state resistance. It is an important parameter for magnet construction and depends primarily on the content and purity of the copper. The procedure for measuring R(295) described in Appendix B is to be used.

The resistance of the wire just above the Nb-Ti superconductor transition temperature and at zero field is termed R(10). The procedure for measuring R(10) described in Appendix B is to be used. The wire residual resistance ratio or RRR is given by the ratio R(295)/R(10).

4. Quality Assurance Provisions:

The vendor shall maintain a quality assurance program to insure that each item offered for acceptance or approval conforms to the requirements herein.

4.1 Requirements of BNL-QA-101

4.1.1 The vendor shall accomplish the following requirements of BNL-QA-101, Brookhaven National Laboratory Seller Quality Assurance Requirements:

| Paragraph in BNL-QA-101 | |
|---|---|
| 3.1 | MIL-I-45208 system specified |
| 4.1 | |
| 4.2 | |
| 4.3 | |
| 4.4 | including 4.4.1, 4.4.2, 4.4.3, 4.4.4 but 30 days before first billet assembly |
| 4.5 | |
| 4.6 | but 30 days before first billet assembly |
| 4.7 | including 4.7.1, and 4.7.2 to be held in file |
| 4.9 | |
| 4.10 | including 4.10.1, 4.10.2, 4.10.3, 4.10.4, 4.10.5 |
| 4.12 | see para. 4.4 of RHIC-MAG-M-4005 and Appendix C. A single copy of the data in electronic form shall be sent to BNL. |
| 4.13 | |
| 4.15 | |
| 4.18 | including 4.18.2 and 4.18.4; see para. 5.4 in this specification. |
| 4.19 | but no changes allowed |
| 4.21 | |
| 4.23 | |

4.1.2 BNL does not grant the Seller material review authority to accept as-is items that do not conform to the requirements of this procurement, or to repair items to a still nonconforming condition.

4.1.3 In the event of conflict between this specification and BNL-QA-101, this specification shall take precedence.

4.2 Data Transmittal: The vendor shall complete and submit to BNL wire measurement data as given in Appendix C. Electronic data transmittal to BNL is required. An acceptable format will be developed by BNL and the vendor.

4.3 Wire Measurement Data and Samples: The frequency of wire measurements is given in Appendix A. A single copy of the data shall be submitted in electronic form to BNL.

4.4 Wire Samples: Ten ft.-long wire samples will be taken from every wire spool and sent to BNL. If that wire spool is one of those selected by the vendor for measurements as described in Appendix A, the sample shall be taken adjacent to the location used for each vendor wire electrical test. Envelopes and labels for the wire samples will be provided by BNL.

5. Preparation for Delivery:

5.1 The wire shall be spooled on a non-metallic spool with a core of a minimum 3 inches diameter. Spool design must be approved in writing by BNL. Each spool shall contain only one continuous length of wire. Wire shall be level-wound so it can be unspooled without crossovers or kinks. The completed spool shall be overwrapped with a cotton tape, or substantially equal non-metallic material, which will prevent damage to the wire while preventing the unwinding of the wire. The spools shall be given a color to be approved by BNL and shall have the RHIC logo applied in a contrasting color.

5.2 Marking/Requirements: Spools and exterior packaging shall be identified on both flanges with the following information in the order shown:

| |
|---|
| "Superconductor Wire for RHIC Helical Dipole Magnets" |
| Specification No. RHIC-MAG-M-8002-A______ |
| BNL Dwg. No. 12000028________ |
| BNL P.O. No. ________________________________ |
| Wire Spool No. ______________________________ |
| Length ____________________________ feet |
| Weight ________________________ pounds |
| Date of Manufacture ___________________ |
| Name of Manufacturer __________________ |

5.3 Wire Identification Numbers: The system for wire identification will be given to the vendor by BNL.

# APPENDIX A
# FREQUENCY OF SAMPLE TESTING

I. Wire Testing

A. Reference: Table I. Wire Dimensional and Mechanical Requirements. All measurements to be completed by the vendor.

| Requirement | Test Frequency |
|---|---|
| Nominal Filament Diameter and Spacing | Demonstration from billet design |
| Number of Filaments | Vendor QC |
| Wire Diameter | Continuous laser micrometer measurements |
| Wire Twist Direction and Pitch | Min. four samples from each prod. unit or 25%, whichever greater |
| Wire Sharp Bend Test | Min. four samples from each prod. unit or 25%, whichever greater |
| Wire Springback Test | Min. four samples from each prod. unit or 25%, whichever greater |
| Wire Surface Condition | Min. four samples from each prod. unit or 25%, whichever greater for visual inspection. Continuous eddy current testing. |
| Wire Minimum Length | Vendor QC |

APPENDIX A (Cont'd)

I. Wire Testing (continued)

B. Reference: Table II. Wire Electrical Requirements.
All measurements to be completed by the vendor.

Note: A wire test specimen shall be delivered to BNL which is adjacent to the location used for each vendor wire electrical test. Also see paragraph 4.5

| Requirement | Test Frequency |
|---|---|
| Wire Critical Current at 5.0T - to satisfy minimum and variation requirements | Min. four samples from each prod. unit or 25%, whichever greater |
| Wire Maximum R(295) | Min. four samples from each prod. unit or 25%, which ever greater |
| Wire Minimum RRR | Min. four samples from each prod. unit or 25%, whichever greater |

Definitions for Wire Testing:

1) A "spool" consists of a continuous (unbroken) length of wire.

2) A "production unit" consists of wire from a common multifilament billet, which goes through identical mechanical and thermal processing.

3) Where a specified number of samples are to be tested from a "production unit", these specimens must be selected from widely separated portions of the "production unit".

4) "Vendor QC" indicates that the Quality Control (QC) of the parameter is the responsibility of the vendor. The vendor must initiate a program to assure control of the parameter within the required tolerance.

5) In order to assure confidence in results from wire sample measurements, in case there is a large number of "spools",it is necessary to require a minimum of four (4) samples be tested from each "production" unit or 25% of the number of "spools", whichever is greater.

# APPENDIX B
# SUPERCONDUCTOR WIRE AND CABLE TEST METHODS

Test Method 8002-1 Wire Sharp Bend Test

Test Method 8002-2 Wire Springback Test

Test Method 8002-3 Verification of Electrical Properties of Superconducting Wire

A. Wire Critical Current Determination

B. Wire R(295) and RRR Determination

Test Method 8002-1 - Wire Sharp Bend Test

1. Purpose:

The purpose of this test is to approximately simulate the deformation to the superconductor wire that may occur during cabling. The sharp bend fixture is made to produce 20% deformation for the wire diameter used.

2. Materials Required:

A 3-inch long sample of wire to be tested

3. Test Equipment:

Wire Sharp Bend Test Fixture or equivalent.

4. Applicable Documents:

None

5. Test Procedure:

5.1 Bend the wire sample in half and place the bend in the slot of the fixture.

5.2 Slide the mating top of the fixture in the slot and squeeze the sample halves together with a bench vise until closed.

5.3 Remove the top of the fixture and loosen the side screw.

5.4 The sample now resembles a hairpin. Examine the bend under 10x magnification to determine if the wire is cracked or deformed. Any indication of cracking or unusual deformation is cause for rejection and must be brought to the attention of BNL.

5.5 Etch the sharp bend sample while stress-free in nitric acid. USE ALL PRECAUTIONS IN HANDLING ACIDS. Examine the sample again with 10x magnification to determine possible filament damage. Any indication of filament damage is cause for rejection and must be brought to the attention of BNL.

Test Method No. 8002-2 - Wire Springback Test

1. Purpose:

This test establishes a standardized method for testing superconductor wire to determine its springback acceptability for cabling.

2. Materials Required:

A 3-1/2 ft. length of superconductor wire to be tested.
Note: Do not bend wire unnecessarily.

3. Test Equipment:

3.1 Springback Test Fixture or equivalent (Fig. 4005-2 #1).
See BNL Dwg. No. 25-718.01-3. This fixture is mounted on a horizontal surface.

3.2 ($1.5 \pm 0.1$) pound weight.

4. Applicable Documents:

None.

5. Test Procedure:

5.1 Prepare one end of wire sample with a 1/2 inch long, right-angle bend and tie the other end securely to a 1.5-pound weight.

5.2 Test the springback fixture to be sure it turns freely.

5.3 Thread the right-angle bend through the test fixture and place in the hole in the spring winder with the locking pin in place.

5.4 Tighten the wire.

5.5 Make sure the right-angle bend is not affecting the "0" reading and the wire is tangent to the spring winding shaft.

5.6 Set "0" on the degree wheel.

5.7 Hang the 1.5-pound weight over the end of the table. Release the clamp. Hold the spring winder handle and pull the locking pin.

5.8 Wind 10 complete turns and replace locking pin. Then tighten wire clamp.

5.9 Hold spring handle and remove locking pin. Gently let the spring unwind and note the number of revolutions.

5.10 Once the spring has stopped, gently touch the spring handle to make sure the spring has equalized and reached its full springback. Do not unwind the spring.

5.11 Note and record the total number of degrees of springback.

5.12 Cut the sample at the wire clamp and the right-angle bend.

5.13 Carefully slide the spring winder out of its bearings and remove the sample.

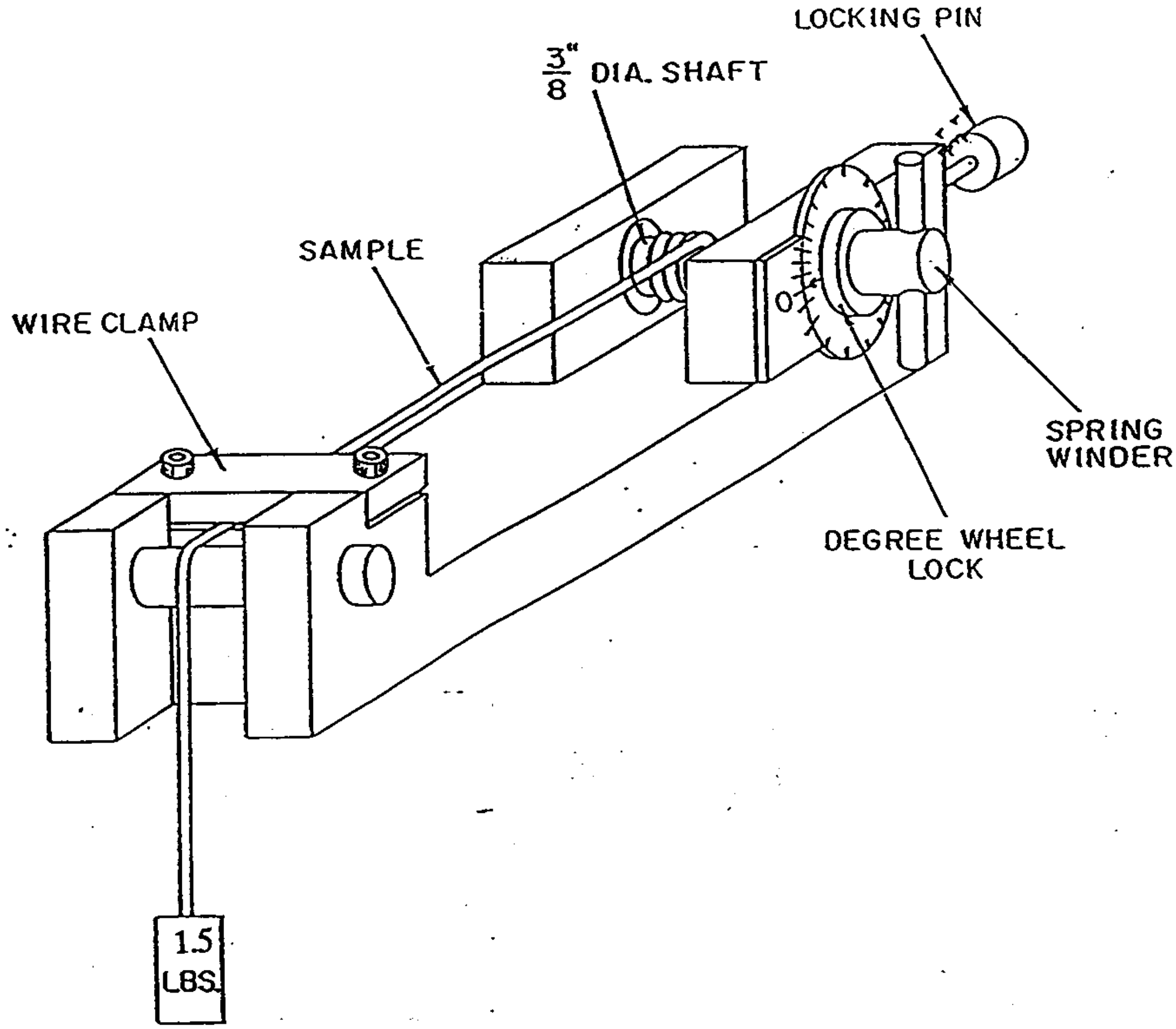


Fig. 8002 #1 Spring-back Test Fixture.

Test Method 8002-3 - Verification of Electrical Properties of Superconducting Wire

A. Wire Critical Current Determination

1. General Outline: Definition of Critical Current

The V-I curve is determined as a function of increasing current until an irreversible transition or quench occurs. This measurement is normally carried out in the specified external field at 5.0T applied normal to the wire axis, and in a temperature bath of liquid helium at 4.2K. However, for sextupole wire the external field is to be both at 2.0 and 5.0T. No correction is made for self-field effects. For currents less than the quench current the V-I curve is reversible.

The critical current, $I_c$, is defined as that at which the resistance per unit length, R, is:

$$R = 10^{-14} /(\pi d^2/4), \text{ ohms/m}$$

where d is the wire diameter in meters. The effective resistivity of the wire is $10^{-14}$ ohm • m at the critical current.

2. Sample Testing

The vendor shall measure the critical current for samples of wire at the specified field value and T = 4.22K. If a temperature of 4.22K is inconvenient, measurements may be made at another temperature and a conversion formula must be supplied. The conversion formula must be approved by BNL. [The notation used here for temperature is as follows: t-in degrees Celsius, T-in degrees Kelvin.]

3. Sample Mounting

The sample wire is most conveniently mounted on a cylindrical grooved form which is made of an insulator, such as G-10, and which fits in a solenoid magnet. (See Section 4 below). The monofilar arrangement, Fig. 4005-3 #1, is used; this lends itself to multiple sample mounting if desired. Voltage taps are arranged as in Fig. 4005-3 #1. Means must be provided for constraint of mechanical motion without interfering with coolant contact: use of a G-10 former with grooved location of wire and careful tensioning during mounting. Care must be taken to ensure that a temperature gradient is not introduced into the region of measurement (gauge length). Care must also be taken in bending the samples, especially at the end of a bifilar sample.

4. Procedure (See Fig. 8002-3 #2)

The sample length (between voltage taps) should be > 25 cm. This corresponds, typically, to a voltage drop of several microvolts at $I_c$. This is readily measured with the aid of a suitable preamplifier or digital voltmeter. Samples of shorter length may be used if a well functioning nanovolt detection system is available. Equipment must be capable of determining the effective resistivity to a precision of 10%.

The voltage signal should be recorded on an X-Y recorder,preferably in a digital memory device. The V-I curve may be taken either point-by-point (current constant for each measurement) or continuously if induced signals due to ramping are not too large or noisy. When the V-I curve is determined by the latter procedure, care must be taken to ensure that there is no rate effect for the ramp rate used. Typically, current is supplied by a stable, well-filtered power supply. The current should be measured to a precision of ± 0.5%. Use of a low resistance normal metal shunt connected across the sample is permitted provided the resulting correction for shunt current is accurately known and is <0.1%. Electronic circuitry for quench protection is preferable.

It is highly desirable that the Quality Index (n) be estimated using the equation $V = \text{constant} \cdot I^{n+1}$. Data points corresponding to ρ-values less than $10^{-14}$ ohm · m will usually be less accurate than those for which ρ is greater than this value. Above $10^{-13}$ ohm · m resistive heating may cause the observed voltage values to be too large. Hence, in fitting a straight line to the log-log plot of the data, the region corresponding to $10^{-14} \leq \rho \leq 10^{-13}$ ohm · m should be emphasized.

5. Magnetic Field

The external field is most conveniently applied by means of a superconducting solenoid. The field must be uniform over the sample reference length to ± 0.5%. The direction between field and wire axis must be $90^o \pm 6^o$ everywhere. This range of angles corresponds to an estimated variation in $I_c$ of <0.5%.

6. Temperature Bath Correction

The specification temperature is 4.22K, that of boiling helium at standard atmospheric pressure. The bath temperature must be recorded with the aid of appropriate thermometry (cryogenic thermometer or vapor pressure of bath) with a precision of ± 0.010K (10mK). Deviations of 20mK or less from 4.22K correspond to an error in $I_c$ of 1% or less and may be ignored. For larger temperature excursions the "linear T" type of correction should be applied:

$$\frac{I_c}{I_t} = \frac{T_c - 4.22}{T_c - T}$$

where $T_c$ is the transition temperature at the specified magnetic field, $I_t$ is the current measured at temperature T, and $I_c$ is the critical current at the specification temperature. At 5T, $T_c$ = 7.2K.

B. Wire R(295) and RRR Determination

1. General Outline: Definition of Residual Resistance Ratio

This method covers the measurement of electrical resistance of Nb-Ti multifilamentary composite wire which is used to make high current superconducting cables. The composite matrix is copper. The resistance per meter is determined at room temperature (295K) and just above the superconductor transition temperature ($T_c$ ~ 9.5K). These quantities are designated R(295) and R(10), respectively, and are measured with an accuracy of 0.5%. The ratio R(295)/R(10) is defined to be the residual resistance ratio, RRR.

R(295) is determined chiefly by the copper matrix. For a given wire diameter it provides a measure of the copper-to-non-copper volume ratio. R(10) is determined chiefly by the residual resistance of the copper matrix and R(295). The ratio RRR provides a measure of the electronic purity of the copper matrix.

2. Apparatus Description

A four-wire method is used to determine the resistance. The wire sample is mounted on a probe which is also used for superconducting critical current measurements. It has leads which are suitable for carrying the required current from room temperature into a liquid helium bath, and potential leads for measuring the voltage drop across a measured length of the test specimen. The probe should be mounted so that the test specimen can conveniently be raised and lowered through the level of a helium bath.

Voltage drops are measured with a voltmeter of 0.5 μV resolution. It is helpful during the low temperature measurement to use an X-Y recorder simultaneously with the digital voltmeter, with Y set to voltage and X to time. (See Section 4 below.)

Currents in the range 0.1 to 1.0A for the R(295) determination and 1 to 10A for the R(10) determination are provided by a well regulated and filtered DC power supply. The current is measured by means of a shunt of 0.25% accuracy.

A thermometer of sensitivity 0.1$^{o}$C is conveniently used for this purpose as an uncertainty of 1$^{o}$C is not accurate enough to determine the copper-to-superconductor ratio to ± 0.01.

3. Sample Mounting

The test specimen is wound on a grooved form. The ends are soldered to the copper terminations of the current leads over a minimum length of 1 inch. Voltage taps are soldered to the specimen at a distance of a least 1 inch from the current joint. Voltage taps are soldered to the specimen at a separation distance of at least 1 inch from each current lead connection. It is advisable that these taps be in the form of fixed pins so that the test length be constant throughout a series of measurements. In order to assure an accuracy of 0.2% in length this length should be ~ 25 cm or more. The voltage leads should follow the sample in a non-inductive fashion so as to minimize noise pickup. Alternatively, the sample may be wound non-inductively on the form.

4. Procedure

Room temperature measurements are made at currents which are a compromise between the requirements of sensitivity and negligible ohmic heating. A typical value is 0.5A. Voltage readings are taken for forward and reversed current and averaged.

Low temperature measurements are made in a helium dewar. The probe is raised so that the lowest point of the specimen is a few centimeters above the liquid helium bath level while measuring current is flowing. After a time of order one second the sample warms above $T_c$(~ 9.5K) and the voltmeter reading suddenly jumps from zero to a finite value corresponding to the sample's normal state resistance. The latter is substantially independent of temperature from the transition temperature, $T_c$, to 15K (residual resistance region), so that the voltage remains constant long enough to be read. When the X-Y recorder is used, a series of abrupt voltage changes are recorded as the specimen is alternately raised and lowered through the helium bath level. The height of these steps should be reproducible.

5. Room Temperature Correction

If the measurements are made at room temperature the differences from 295K necessitate a temperature correction. Designating the observed resistance as R and the ambient temperature as t(°C), the resistance at the reference temperature of 295K is calculated as follows:

$$R(295) = R/[1 + 0.0039\,(t - 22)]$$

The effect of the Nb-Ti is negligible for the purpose of this correction.

6. Cu/SC Ratio Calculation

The copper: superconductor volume ratio (x) is calculated from R(295) and RRR by means of the formula

$$X = \frac{1 - R(295)\ A/\rho_S}{R(295)\ A/\ \rho_{cu} - 1}$$

where R(295) = resistance of the cable at 295K in ohms/m

$\rho_{cu}$ = resistivity of the copper at 295K, in ohm • m

$$= \rho_i \frac{RRR}{RRR - 1}$$

$\rho_i$ = resistivity of pure copper at 295K

$= 1.695 \times 10^{-8}$ ohm • m

$\rho_s$ = resistivity of Nb-Ti at 295K

$= 60 \times 10^{-8}$ ohm • m

and A = wire cross section area in $m^2$

$= \pi d^2/4$ (d = wire diameter in m)

Reference: "Normal State Resistance and Low Temperature Magnetoresistance of Superconducting Cables for Accelerator Magnets" by W.B. Sampson, M. Garber and A.K. Ghosh, IEEE Trans. on Mag. 25, 2097-2100 (1989).

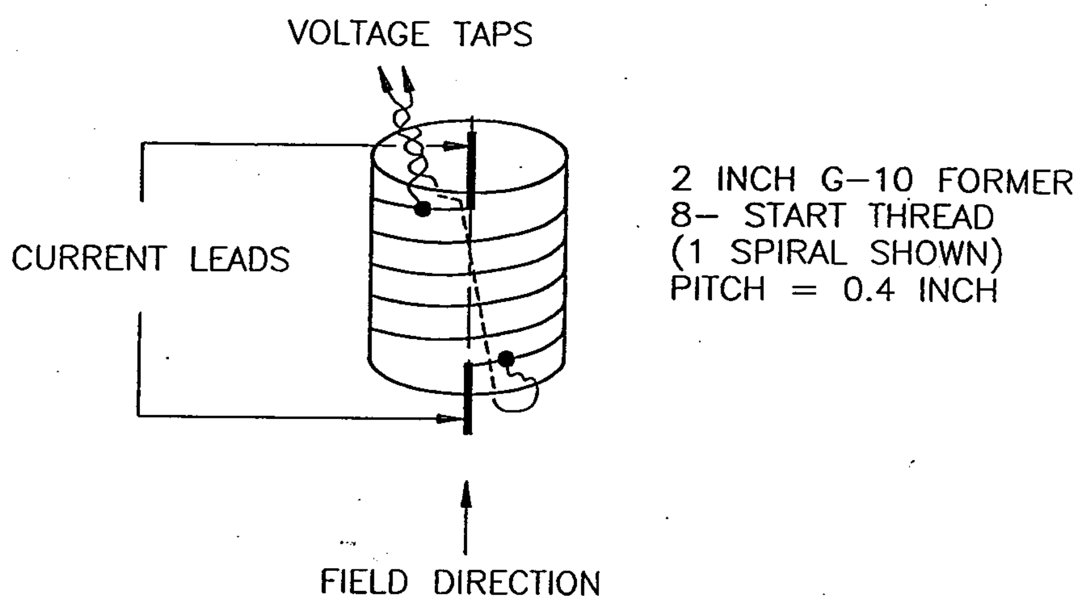


**FIG. 4005-3 #1 SAMPLE MOUNTING ARRANGEMENT**

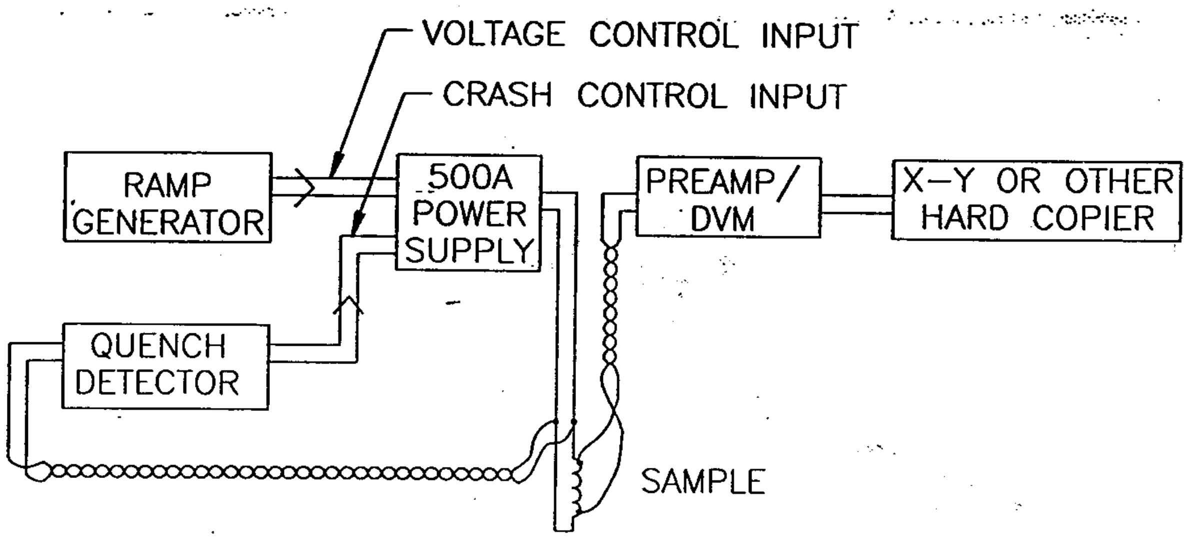


**FIG. 4005-3 #2**

**SCHEMATIC OF ELECTRICAL MEASUREMENT APPARATUS**

SK/S00336BS

IEEE TRANSACTIONS ON MAGNETICS, VOL. 25, NO. 2, MARCH 1989

# NORMAL STATE RESISTANCE AND LOW TEMPERATURE MAGNETORESISTANCE OF SUPERCONDUCTING CABLES FOR ACCELERATOR MAGNETS*

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Brookhaven National Laboratory,
Upton, New York 11973

## Abstract

The normal state resistivity of the superconducting NbTi cable used in accelerator magnets is usually specified by the resistance per unit length at room temperature (295 K) and the residual resistance ratio (RRR). Using these resistance parameters, the amount of copper in the multifilamentary wire can be calculated. This method is consistent with the traditional etch and weigh technique, and as such is a alternative and convenient way of specifying the copper to superconductor ratio. In principle the magnetoresistance can be calculated from the RRR and the "Kohler Plot", for copper. In practice however, measurements of magnetoresistance for a wide variety of SSC inner cables show considerable disagreement with calculation. In this paper the magnetoresistance data on cables with RRR ranging from 50 to 175 are analyzed taking into account the conductor geometry and the effect of the small interfilamentary spacing on the resistivity of copper.

## Introduction

The electrical resistance of the multifilamentary NbTi wire which is used to make superconducting magnet cable is routinely measured at 295 K and 10 K. From these two measurements can be determined the amount and purity of the copper in the wire. Similar measurements are also made on the effect of transverse magnetic fields on the normal state resistance of the cable. These normal state resistances are relevant in determining quench propagation characteristics and the maximum temperature reached in the coil windings of a magnet during a quench. In the first part of this paper we discuss the relationship between the room temperature measurement and the amount of copper in the superconducting wire. The second part deals with the transverse magnetoresistance of SSC prototype cables.

## Resistance and Copper to Superconductor Ratio, Cu/Sc

In this section we examine the quantitative relationship between the resistance and the copper to superconductor ratio, X. A study of CBA wires with a nominal X of 1.7 has been reported by Garber et. al.[1] In the present report, wires from several sources with X values ranging from 1 to 3 were examined. Resistances and critical currents were measured on 75 cm long samples. Two 25 cm pieces were then cut from each sample for the mass determination as outlined below.

The copper to superconductor ratio is defined in terms of the volumes of the respective components. It can be calculated from four quantities: A, the area of cross section; m, the wire mass per unit length; $m_S$, the mass of NbTi per unit length, and $\delta_{cu}$, the density of copper. The superconductor mass was determined by weighing after etching away the copper matrix. Each sample was weighed three times: before etching, after a 15 minute etch in 50% nitric acid solution and after a second 15 minute etch, to make certain that all the copper was removed. Weight readings before and after the second etch agreed to with ≈ 0.1 mg. This corresponds to ±0.5% in $m_S$. The copper to superconductor ratio, $X_m$, is calculated from,

$$X_m = \left(\frac{A\,\delta_{cu}}{m-m_s} - 1\right)^{-1} \quad (1)$$

The room temperature resistance $R_t$ is measured at ambient temperature t(°C), and the resistance at the reference temperature of 295 K is calculated from:

$$R = R_t/[1+0.0039\ (t-22)] \quad (2)$$

The low temperature resistance $R_{10}$ is measured just above the transition temperature of NbTi. The residual resistance ratio r is then defined as

$$r = R/R_{10} \quad (3)$$

The room temperature resistance can be written as,

$$\frac{1}{R} = \frac{X}{(1+X)}\frac{A}{\rho_{cu}} + \frac{1}{(1+X)}\frac{A}{\rho_s} \quad (4)$$

or,

$$X = \frac{1 - RA/\rho_s}{RA/\rho_{cu} - 1} \quad (5)$$

where $\rho_{cu}$ is the copper resistivity at 295 K and $\rho_S$ is the resistivity of NbTi ~ 60 μΩ/cm. Variations in $\rho_{cu}$ due to impurities may be approximated by

$$\rho_{cu} = \rho_i \frac{r}{r-1} \quad (6)$$

where $\rho_i$ = 1.695 μΩ-cm is the resistivity of pure copper.

If the low temperature resistance is not known a value of $\rho_{cu}$ of 1.71 μΩ-cm can be used which is equivalent to an RRR of approximately one hundred, a typical value for composite wire.

Figure 1 shows the copper to superconductor ratio $X_R$ as derived from resistance measurements plotted against that obtained by mass determination $X_m$. For some samples $X_R < X_m$ probably due to variations in cross sectional area. This "sausaging" of the filaments has been observed in microstructural studies and is correlated with the low n-values indicative of non-uniform filaments.[2]

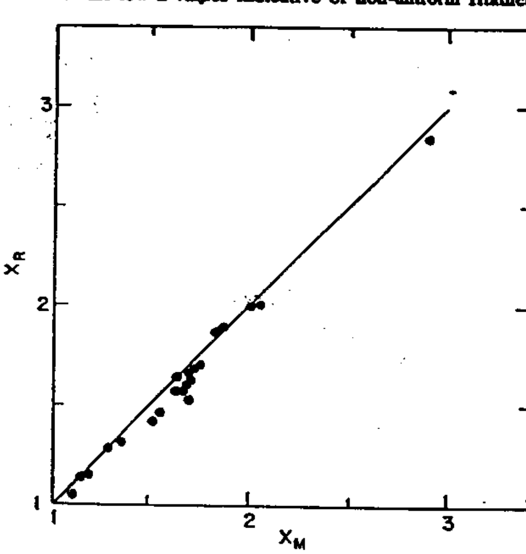


Fig. 1. Resistive determination of Cu/Sc, $X_R$, plotted versus mass determination, $X_m$.

*Work performed under the auspices of the U.S. Department of Energy
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Resistance Specification for Superconducting Wires

Using eq. (5), the resistance of wires of different diameters can be calculated as a function of Cu/Sc ratio. This is shown in Fig. 2 for the wires used in SSC cables. The range of acceptable values of R is determined by the Cu/Sc ratio and wire diameter tolerances. The above calculations can be extended to cables. In applying these formulae the cable resistance is multiplied by N, the number of wires and a length correction factor applied.

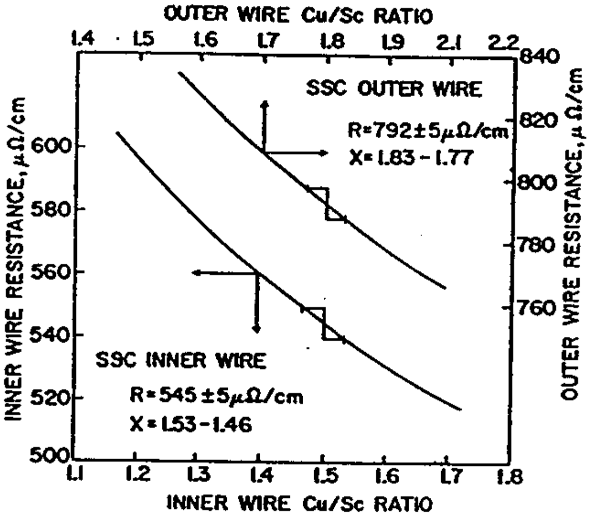


Fig. 2. Plot of resistance per cm for SSC inner and outer wires as a function of copper to superconductor ratio.

Transverse Magnetoresistance of Superconducting Cables

In this section we present magnetoresistance data on some SSC cables. We show that the measurements on conductors with very small NbTi filaments agree with the magnetoresistance of bulk copper provided size effect enhancement of the copper resistivity in the interfilamentary region is taken into account.

Test Procedure for Cables

The room temperature resistance measurement is made using a DC current of 1 A, and voltage contacts 70 cm apart (see Fig. 3). A thermocouple device of 0.1°C accuracy is used to determine the ambient temperature. Temperature correction to 295 K is made using eq. (2).

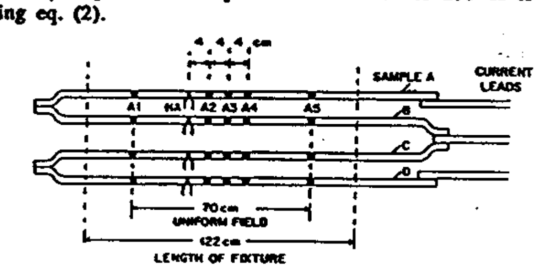


Fig. 3. Electrical wiring schematic experimental arrangement for determination of cable resistance.

The low temperature measurement is a dynamic one, made by inducing a quench when the cable is carrying current. Referring to Fig. 2, a quench is triggered in cable A, for example, by means of heater HA. The resulting waveform observed at nearby voltage taps, A2-A3 or A3-A4, consists of three parts: a superconducting state baseline voltage, a linear ramp voltage corresponding to the passage of the superconducting-normal interface between the voltage taps, and a slowly increasing signal characteristic of the normal state resistance. The latter increases in time due to normal state heating. However, at first the voltage is almost constant and is due to the residual resistance of the copper. Thus, there is a kink in the voltage waveform at the beginning and at the end of the linear ramp portion. The voltage difference between these two points equals the current times the residual resistance of the section of cable between the voltage taps. The resistance per centimeter is determined for two pairs of taps (A2-A3 and A3-A4 in Fig. 3) and averaged. The taps are relatively close to the heater in order to minimize the effect of current fall-off which results from the increase of normal state resistance as the quench propagates.

The above measurement is made at zero field and in an external transverse field in order to determine the magnetoresistance effect. The longitudinal quench propagation velocity can be deduced from the same test.

Experimental Data

Like copper, the magnetoresistance of the cables was found to be linear with field in the range 1 < H < 6 tesla. Figure 4 shows the data for some of the cables that were studied. Considerable variation in the low temperature resistance is possible even for cables with the same Cu/Sc. Cable SC368A is similar to SC368B except the former was annealed after cabling. Table I lists the cables and their relevant geometric parameters.

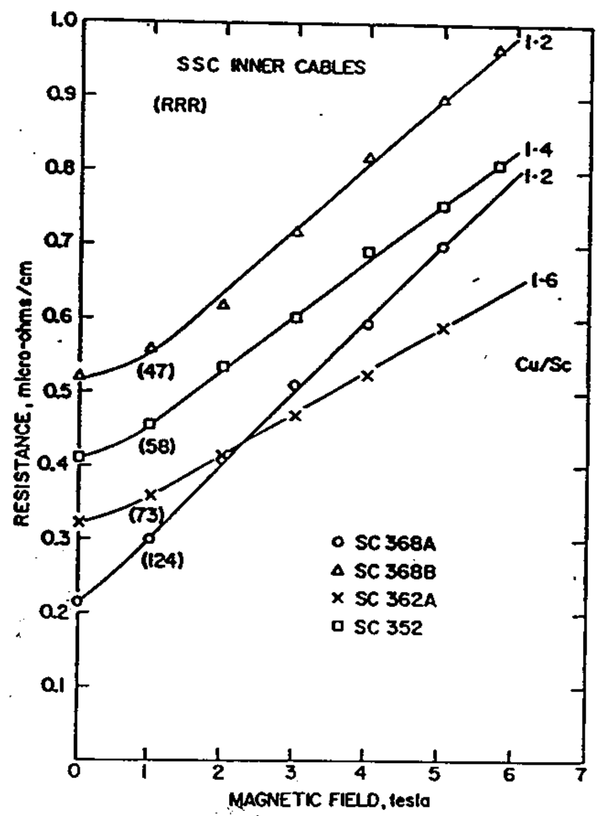


Fig. 4. Resistance per unit length of SSC prototype cables as a function of applied magnetic field.

From a magnet designer's point of view the quantity of interest is the resistance at field which is given in Fig. 5, as the ratio of the resistance of 6T to that at zero field plotted vs the measured RRR. The solid line reflects recent data at 4.2 K for oxygen-free copper as compiled by Fickett.[3,4] Clearly, for the conductors which have filaments with diameters, d ~ 5 μm, the measured magnetoresistance is higher than that predicted by the bulk copper data.

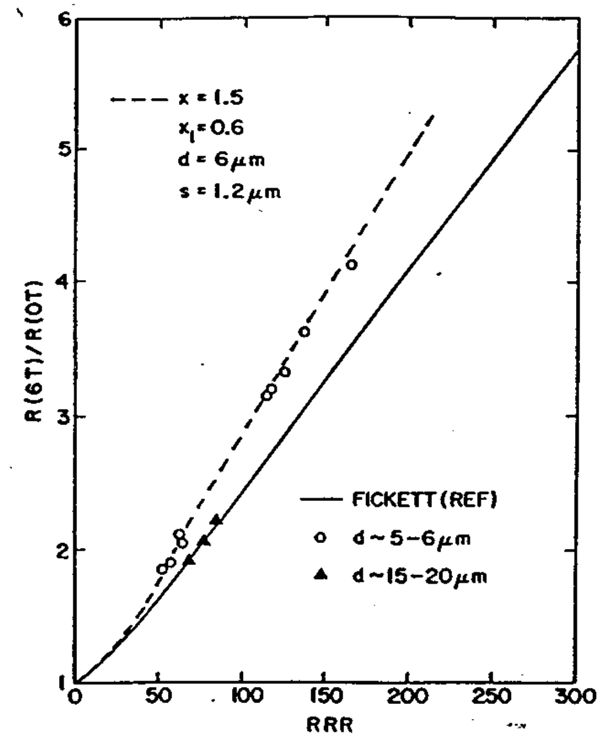


Fig. 5. The ratio of resistance at 6 tesla and at 0 tesla of SSC cables as a function of the measured RRR. The solid line is Fickett's[3,4] data for bulk copper.

Size Effect in Multifilamentary Superconducting Wires

The discrepancy between the predicted and measured values of magnetoresistance can be reconciled by taking into account the resistivity enhancement in copper due to the so called "size effect". This becomes important when the bulk electronic mean free path, $\ell$ becomes comparable to some sample dimension. The boundary scattering of electrons in effect reduces the scattering length and thereby increases the resistivity. Brändli and Olsen[5] have written a detailed review of this effect and more recently Cavalloni et. al.[6] have presented experimental evidence for the existence of a size effect on the longitudinal resistivity of multifilamentary superconducting wires.

Although there are several expressions for the resistivity enhancement the simplest one, by Nordheim,[5] is the one we shall use. In the copper-stabilized wires there are usually two regions: (a) those which are free of filaments and (b) those consisting of a array of NbTi filaments. The surfaces of the NbTi filaments act as boundary scatterers, and the copper in the interfilamentary region has a higher resistivity when $\ell$ is greater than the interfilament spacing, S. Assuming diffuse scattering at the NbTi interface, the resistivity of the copper can be represented by;

$$\frac{\rho_I}{\rho_0} = 1 + (1/K) \qquad (7)$$

In this case $K = S/\ell < 1$ and $\rho_0$ is the residual resistivity of (a) and $\rho_I$ the resistivity of (b). At 295 K, $\ell << S$ and the size effect is unimportant. Equation (7) can be written as:

$$\frac{r_I}{r_0} = \left(1 + \frac{\ell}{S}\right)^{-1} \qquad (8)$$

where $r_I$ is the RRR of region (b) and $r_0$ is the RRR of the region (a). The mean free path can be calculated from[7] $\rho\ell = 6.56 \times 10^{-12} \Omega$ -cm$^2$. From this the $\ell = 0.0387\, r_0$ μm. Using this in eq. (8) we find that

$$r_I = r_0\left(1 + \frac{0.0387}{S} r_0\right)^{-1} \qquad (9)$$

The interfilament spacing, S, is related to the local Cu/Sc ratio, $X_L$, by

$$X_L = 1.1(1 + S/d)^2 - 1 \qquad (10)$$

where S and d, the filament diameter, are in microns. Using the geometric paramenters X, $X_L$, and d, and the measured value of r, we can calculate $r_0$ and $r_I$. These are given in Table I. For large filament conductors similar to those studied by Cavalloni et. al.,[6] the ratio $(r_0/r_I) \sim 2$. However in fine filament conductors with small S values this ratio can be much higher. Thus if the RRR of the bulk copper is 100 the RRR of the copper between the filaments is only 20. Furthermore if the bulk copper is improved to 200 by annealing the interfilament copper ratio only increases to 23 for a conductor with a one micron filament spacing. A simple calculation leads to the residual resistivity ratio of the composite:

$$r = [(X - X_L)\, r_0 + X_L r_I]/X \qquad (11)$$

and r is always less than $r_0$

Now if we assume that in field, the copper increases in resistivity in accordance with its respective RRR, then the ratio of the resistance at 6 tesla to that in zero field can be determined by reference to the bulk copper curve of Fig. 5. The dashed curve in Fig. 5 was calculated for X = 1.5, $X_L$ = 0.6, S = 1.2 μ and d = 6 μ.

Table 1

| Cable Sample | Wire Dia. mm | Cu/Sc,X | Filament Dia. μm | Local Cu/Sc,$X_L$ | RRR $r$ | RRR $r_0$ | RRR $r_I$ | $r_0/r_I$ | S μm | R(6T)/R(0T) Meas. | R(6T)/R(0T) Cal. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SC357 | 0.81 | 1.45 | 5 | 0.45 | 166 | 232 | 17.9 | 13.0 | 0.75 | 4.12 | 4.20 |
| SC368A | 0.81 | 1.2 | 6 | 0.50 | 125 | 198 | 22.8 | 8.7 | 1.0 | 3.32 | 3.47 |
| SC368B | 0.81 | 1.2 | 6 | 0.50 | 53 | 77 | 19.3 | 4.0 | 1.0 | 1.85 | 1.85 |
| SC368B1 | 0.81 | 1.2 | 6 | 0.50 | 136 | 248 | 27.5 | 9.0 | 1.0 | 3.65 | 3.70 |
| FG6218 | 0.81 | 1.28 | 4.7 | 0.45 | 116 | 171 | 16.6 | 10.3 | 0.7 | 3.20 | 3.26 |
| SC363 | 0.81 | 1.6 | 20 | 0.45 | 79 | 94 | 46 | 2.0 | 3.0 | 2.01 | 2.14 |
| SC347A | 0.81 | 1.33 | 5 | 0.8 | 115 | 241 | 31 | 7.7 | 1.4 | 3.15 | 3.39 |
| SC347A1 | 0.81 | 1.33 | 5 | 0.8 | 57 | 102 | 26.7 | 3.8 | 1.4 | 1.90 | 1.96 |
| SC352 | 0.81 | 1.60 | 5 | 0.45 | 62 | 80 | 15.6 | 5.1 | 0.75 | 2.10 | 2.00 |
| SC362 | 0.81 | 1.40 | 6 | 0.5 | 64 | 89 | 20 | 4.5 | 1.0 | 2.05 | 2.04 |
| XT-12 | 0.81 | 1.3 | 23 | 0.8 | 69 | 86 | 58 | 1.5 | 6.9 | 1.90 | 1.94 |
| SO118 | 0.65 | 1.8 | 15 | 0.6 | 84 | 104 | 44 | 2.4 | 3.0 | 2.20 | 2.25 |

the parameters for the SSC inner cable. Measured values of the $R_6/R_0$ ratio for conductors of this type, the open points in Fig. 5, agree with the calculated curve to a remarkable degree. Conductors with larger filaments and therefore larger filament spacing, the solid points, are almost indistinguishable from bulk copper.

## Conclusions

Resistance measurements which are rountinely made on superconducting wires and cables for accelerator magnets can provide an accurate measure of the copper to superconductor ratio. Compared to the etch and weigh technique a resistance specification for Cu/Sc is preferable for monitoring of this parameter during wire and cable production.[8]

Results shown here indicate that by using the 4 K magnetoresistance data of bulk copper and the size effect formula for the resistivity enhancement of copper, the measured RRR can be used to estimate the resistance at high fields.

## Acknowledgements

We thán Dr. R.P. Shutt for several discussions and for initially pointing out the discrepancy from the "Kohler Plot".

## References

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[2] M. Garber, M. Suenaga, W.B. Sampson and R.L. Sabatini, "Critical current studies on fine filamentary NbTi accelerator wires," Adv. in Cryo. Eng.-Mater., vol. 32 (Plenum Press, New York, 1986), pp.

[3] F.R. Fickett, "Transverse Magnetoresistance of oxygen-free copper," IEEE Trans. on Magnetics, 24 (1988), pp. 1156-1158.

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[5] G. Brandli and J.L. Olsen, "Size effect in electron transport in metals," Mater. Sci. Eng. 4, (1969), pp. 61-83.

[6] C. Cavalloni, K. Kwasnitza, R. Monnier and L. Horvath, "Size effect of the longitudinal resistivity of multifilamentary superconducting wires," Appl. Phys. Lett. 42(8), 1983, pp. 734-736.

[7] F.R. Fickett, "Electronic Properties", in Materials at Low Temperatures, ASM, Metals Park, 1983, pp. 178-179.

[8] P. Dubots, P. Genevey, J. Goyer, J.C. Renard and A. Sagniez, "Continuous determination of the cross section area of the components of a niobium-titanium superconductor," Cryogenics, 23, (1983), pp. 495-497.

# APPENDIX C
# WIRE MEASUREMENT DATA

On the sheets to follow are summarized the data transmittal for measurement information from the vendor to BNL. It is only necessary for the vendor to supply the data as given in Appendix A. The vendor will coordinate with BNL the regular transmittal in electronic form either on 3-1/2 inch or 5-1/4 inch floppy discs in any density. The file structures listed below can easily be imported into R:Base at BNL and are listed in order of preference.

1. R:Base
2. ASCII delimited
3. ASCII fixed
4. Lotus 1-2-3 (.WKS)
5. Excel (.XLS)
6. dBASE (.DBF)
7. pfs:FILE
8. DIF
9. Multiplan (SYLK)
10. Another system to be agreed upon by BNL

APPENDIX C (Cont'd)

**Wire Mechanical Data**

Wire Identification
Wire twist direction (Left/Right)
Wire twist pitch (twists per inch)
Sharp bend test (Pass/Fail with comment)
Springback (degrees)
Surface condition (Pass/Fail with comment)
Cu/Sc ratio by chemical method (if used)
Comments

**Wire Electrical Data**

Wire Identification
Date of tests
Run number
Ic at 2.0T
Ic at 5.0T
n at 2.0T
n at 5.0T
Iq at 2.0T
Iq at 5.0T
Jc at 2.0T
Jc at 5.0T
R(295)
RRR
Cu/Sc ratio by electrical method
Comments

**Wire Production Data by Vendor**

Wire Identification
Wire length (feet)
Wire weight (lb.)
Diameter - Minimum
Diameter - Maximum
Diameter - Average
Diameter - Standard deviation
Diameter - Data points
Comments

BNL P.R./P.O. NO. RHIC-MAG-M-4005

BNL-QA-101
January 2, 1987

# BROOKHAVEN NATIONAL LABORATORY
# SELLER QUALITY ASSURANCE REQUIREMENTS

## 1.0 SCOPE

1.1 This document, when invoked by purchase order or contract, establishes quality assurance requirements to which sellers to Brookhaven National Laboratory (BNL) shall conform during the performance of work required by the purchase order, or contract.

1.2 This document contains two main sections. Section 3.0 covers the general requirements that are applicable to all sellers. Section 4.0 contains special quality assurance requirements that are applicable only when specifically invoked by the purchase order.

## 2.0 DEFINITIONS

2.1 The term *Purchase Order* means the purchase order, contract, subcontract or other written agreement with the Seller (supplier) in which the requirements of this document are incorporated by reference.

2.2 The term *Buyer* means Associated Universities, Inc. operating Brookhaven National Laboratory, acting by and through its Division of Contracts & Procurement issuing the purchase order.

2.3 The term *Seller* means the legal entity which is the contracting party with the Buyer with respect to the purchase order.

## 3.0 GENERAL REQUIREMENTS

Unless otherwise specified in the purchase order, the following General Requirements apply:

### 3.1 Seller Quality Assurance Program/Inspection System

The Seller shall have and maintain an effective quality assurance program or inspection system that will, as a minimum, comply with all of the requirements of the specification designated below:

☐ 3.1.1 MIL-Q-9858 "Quality Program Requirements" (Latest revision as of the date of purchase order issuance).

☒ 3.1.2 MIL-I-45208 "Inspection System Requirements" (Latest revision as of the date of purchase order issuance).

In the specifications designated above add "Brookhaven National Laboratory" wherever the word "Government" appears.

☐ 3.1.3 Conformance to Manufacturer's Specifications.

***Note:** In the event that Requirement 3.1.1 or 3.1.2 is specified, and the Seller's quality assurance program or inspection system does not comply with the specified requirement, the Seller shall submit with his quotation a description of his existing quality assurance program or inspection system that will apply to this order. The description will be evaluated by the Buyer prior to award.*

### 3.2 Audit by Buyer

The Seller's Quality Assurance Program or Inspection System shall be subject to audits by the Buyer's Representative(s) for conformance with the requirements of the purchase order.

### 3.3 Conformance to Requirements

All items furnished to the Buyer shall conform in every way with all requirements of the purchase order. No change(s) shall be made to any Buyer requirements without the prior approval of the Buyer.

### 3.4 Responsibility for Conformance

Neither audits, surveillance, inspection and/or tests made by the Buyer or its representatives at either the Seller's or Buyer's facility, nor the Seller's compliance with all applicable Quality Assurance Requirements shall relieve the Seller of the responsibility to furnish items which conform to the requirements of the purchase order.

### 3.5 Protection of Material and Equipment

The Seller shall employ procedures which assure adequate protection of material and equipment during shipment and while in storage. Such protection shall include special environmental packaging, as necessary.

### 3.6 Certification of Conformance

By making shipment under this purchase order, the Seller automatically certifies that the articles shipped, the materials (except when the materials are furnished by the Buyer) used in the articles shipped, and the processes applied to such articles comply with the applicable drawings, specifications and requirements of the purchase order. The Seller agrees to retain objective evidence, including records, of the inspections and tests performed in the course of manufacturing, testing, inspecting, preserving, packaging, and preparation for shipment of said articles. These records shall be made available to the Buyer's representative for review upon request.

### 3.7 Measuring and Test Equipment Calibration

The Seller shall establish and maintain a documented system for the calibration of measuring and test equipment used in the fulfillment of the purchase order requirements. As a minimum, the Seller shall calibrate measuring and test equipment against certified standards which have known valid relationships to national standards. The calibrations shall be performed at established periods to assure measuring and test equipment accuracy at the time of use.

## 4.0 SPECIAL REQUIREMENTS

The following Special Requirements are applicable only when specifically invoked by purchase order, or as indicated by checkmark hereon.

☒ 4.1 Q.A. Plan or Manual: The Seller shall submit a copy of his Quality Assurance Manual or Plan with his proposal for review and evaluation.

☒ 4.2 Configuration Control System: The Seller shall establish and maintain a system to assure that all end items (including spares) are of the proper configuration, and that all approved configuration changes are incorporated at the specified effectivity points. Records shall be maintained verifying the configuration of each item.

☒ 4.3 Process Sheets, Travelers, etc.: The Seller shall maintain a system of process sheets, shop travelers, or equivalent means to define the sequence of manufacturing, inspection, installation and test activities to be performed. Flow sheets, or equivalent, shall provide for sign-off by designated inspection personnel at specified inspection and test points, to assure completion as well as proper sequencing of required operations.

☒ 4.4 Manufacturing/Inspection/Test Plan: Sixty (60) days prior to fabrication the Seller shall prepare and submit for the Buyer's review and approval a manufacturing/inspection/test plan for the item(s) to be produced, which satisfies the following:

☒ 4.4.1 Identification of parts and subassemblies showing integrated flow into end item(s).

☒ 4.4.2 Identification of critical manufacturing operations as well as inspection and test checkpoints.

☒ 4.4.3 The Plan may be a single document, or may make use of existing "travelers", or other suitable planning and control documents.

☒ 4.4.4 Revisions or changes to the Buyer approved Plan must be submitted for the Buyer's review and approval prior to implementation.

☒ 4.5 "Witness" Points: The Buyer reserves the right to designate selected manufacturing, inspection, and/or test operations as "witness" points. The Seller shall provide the Buyer with five (5) working days notice in advance of reaching such witness points during the manufacturing and test cycle of each item.

☒ 4.6 Test and Inspection Procedures: Test and inspection procedures required to demonstrate satisfactory completion of purchase order requirements shall be prepared by the Seller and submitted to the Buyer for review and approval sixty (60) days prior to use of such procedures.

☒ 4.7 Special Process Procedures: Special processes (e.g. welding, brazing, bonding, plating, chemical machining, chemical coating, chemical cleaning, precision cleaning, heat treating, radiographic inspection, ultrasonic testing, pressure or leak testing) shall be performed in accordance with detailed written procedures. These procedures shall specifically describe the exact manner in which the processes are to be performed.

☒ 4.7.1 Copies of special process procedures shall be available for review by the Buyer's representative upon request.

☒ 4.7.2 At least sixty (60) days prior to use on items deliverable to the Buyer, the Seller shall submit to the Buyer copies of all applicable process procedures for review and approval. Revisions or changes to Buyer approved special process procedures must be submitted to the Buyer for review and approval prior to implementation.

☐ 4.8 Qualification of Special Process Procedures, Facilities and Equipment: The Seller shall, prior to use, qualify the procedures/specifications, facilities and equipment that will be used for the performance of special processes. Records of such qualification shall be available to the Buyer's representative upon request.

☒ 4.9 Qualification of Special Process Personnel: The Seller shall provide for the qualification of personnel, prior to their use, to ensure competence in the use of the special process procedures or specifications. Records of such qualification shall be available to the Buyer's representative upon request. Only those personnel who have been qualified to perform a specific special process shall be used to perform that process.

☒ 4.10 End Item Documentation Package: The Seller shall provide a documentation package for each item supplied, which consists of objective evidence of compliance with purchase order requirements. This documentation package shall be complete, legible, indexed, and traceable to the item supplied, and shall contain the following, as applicable:

☒ 4.10.1 Copies of reports of all required or necessary inspections, examinations and tests, properly validated by the Seller's authorized personnel.

☒ 4.10.2 A listing of the as-built configuration of each delivered item; this may be defined by the use of drawing numbers and revisions, unique parts lists or other such means of positive identification.

☒ 4.10.3 Copies of nonconformance reports dispositioned as "repair" or "use-as-is".

☒ 4.10.4 Copies of material test reports for specified materials, showing physical and chemical properties.

☒ 4.10.5 A Certificate of Conformance (See 4.16).

☐ 4.11 Release for Shipment: The Seller shall provide the documentation package required in 4.10, for review by the Buyer's representative prior to release of the item for shipment.

☒ 4.12 Shipment of Documentation Package to Buyer: Three (3) copies of the documentation package shall be shipped to the Buyer with or prior to shipment of the purchased items.

☒ 4.13 Failure Reporting, Analysis, and Corrective Action: The Seller shall maintain a failure reporting, analysis and corrective action program to determine and report what reliability or safety problems may exist in the equipment, define their nature and cause, and recommend and implement the necessary corrective actions.

The Seller's failure reporting, analysis, and corrective action program shall, as a minimum, evaluate and analyze failures occurring during qualification, first article and end-item acceptance testing and inspection. To determine the true cause of failure, the analysis should include, as appropriate, the disassembly or dissection of the failed item(s). The results of all failure evaluations and analyses shall be documented.

☐ 4.14 Source Inspection/Surveillance: Items to be delivered under this purchase order require inspection, tests or surveillance by the Buyer's representative at the Seller's facility. Five (5) work days notice of acceptance inspections and tests shall be given by the Seller to the Buyer to permit scheduling of source inspection.

☒ 4.15 Chemical and Physical Test Report: One copy of actual chemical and physical test report(s) for each heat, batch or lot shall accompany each shipment. Test reports shall list the actual parameters tested, and shall contain the actual readings taken during test.

☐ 4.16 Certificate of Conformance: With each shipment of items covered by this purchase order, the Seller shall submit a certificate of conformance. In case of drop shipment, a copy of the certificate shall be submitted to the Buyer at the time of shipment. The certificate shall be signed by an officer of the company, and shall constitute a representation by the Seller that:

A. Materials used are those which have been specified by the Buyer, and that the items delivered were produced from materials for which the Seller has on file reports of chemical or physical analysis, or any other equivalent evidence of conformance of such items to applicable specifications;

B. Processes used in the fabrication of items delivered were in compliance with applicable specifications forming a part of the purchase order, or Buyer approved procedures or specifications;

C. The items as delivered comply with all specifications and other requirements of the purchase order.

☐ 4.17 Report with Each Shipment: The Seller shall submit with each shipment a report for the delivered end items or assemblies with the following information included as a minimum: part number, revision letter of as-built part, nomenclature, purchase order number, serial numbers or lot number, lot quantity, inspection sample size, characteristics/parameters inspected and/or tested, inspection/test data, date of inspection/test, and signature/stamp of Seller's inspection/test representative. If Go/No-Go test method is used, test program must be identified.

In case of drop shipment, a copy of the report shall be submitted directly to the Buyer at time of shipment.

☒ 4.18 First Article Acceptance: Buyer acceptance of first article(s) is required prior to the production run. The first article(s) shall be identified as such, including the purchase order number, part number and part name. The Seller is required to:

☐ 4.18.1 Submit the first article(s) to the Buyer's representative for test/inspection to be conducted at the Seller's facility by the Buyer's representative;

☒ 4.18.2 Submit the first article(s) to the Buyer for test/inspection by the Buyer at the Buyer's facility;

☐ 4.18.3 Submit the first article(s) to the Buyer together with documents showing data representing results of the Seller's first article(s) test/inspection, including the actual dimension or value for each specified characteristic;

☒ 4.18.4 After Buyer acceptance of first article(s) all of the remaining units required by the purchase order shall be produced by the Seller and the Seller's suppliers using the same design, materials, processes, methods and tooling that were used to manufacture the approved first article(s). Any changes must have prior approval from the Buyer.

☒ 4.19 Notification of Change to Design, Methods, or Processes: The Seller shall immediately notify the Buyer of any significant changes (those that may effect form, fit, function, reliability, safety or interchangeability) in product design, fabrication methods, material or processing from those used by the Seller at time of Seller's quotation or offer to the Buyer, which resulted in the purchase order.

☐ 4.20 Age/Shelf Life and Storage Control: The Seller shall have an effective storage and age control system for items whose acceptability is limited by the age or manner of storage of the item. The system must include a method of identifying the age of such items, and provisions for the rotation and purging of stock.

The Seller shall show on each container of materials having a limited or specified shelf life (both Seller's in-plant containers and containers in which material is delivered to the Buyer) the cure or manufacture date, expiration date, lot or batch number, and special storage and handling conditions applicable to the contents. This information shall be in addition to the normal identification requirements of name, part or code number, specification number, type, size, quantity, etc. Special handling conditions shall be recorded on certifications and shipping documents covering the material delivered to the Buyer.

Time lapse between cure or manufacturing date and date of receipt by Buyer shall not exceed one-quarter of the shelf life for the material without a prior written waiver from the Buyer for each shipment.

☒ 4.21 Serial Numbers: The Seller shall assign a separate and distinct serial number to each end item furnished under this purchase order. Where impractical to stamp individual items due to size or shape, the serial number shall be stamped on identifying tags or the smallest unit package. No two items having the same part number are to be identified with the same serial number. Records of serial numbers for each part number must be maintained by the Seller.

☐ 4.22 Lot or Batch Numbers: For items furnished under this purchase order, the packing list, certifications and other applicable documents must be identified by manufacturing lot or batch number. Where impractical to stamp individual parts due to size or shape, the lot or batch number shall be stamped on identifying tags or the smallest unit package.

☒ 4.23 Material Traceability: Materials used must be identified by material type, applicable specification and revision number, and be tracable to their lot number(s) and heat number(s). Traceability records shall be available for review by the Buyer's representative.

☐ 4.24 Shipment Destination Other than BNL: The material ordered against this purchase order is to be shipped to other than the Buyer's facilities. Copies of the Quality Assurance data required by this order shall accompany the shipment; in addition, one copy of such data shall be mailed to the Buyer on the same day that shipment is made.

☐ 4.25 Heat Treat Bars: Two heat bars shall be heat treated with the parts from each heat treat lot and submitted to the Buyer with the shipment. The bars shall be identified with the heat lot number, and the date of heat treatment.

☐ 4.26 Burn-in: Burn-in shall be accomplished on each completed item to be delivered to the Buyer. The items will be burned-in for a continuous 96-hour period at nominal operating power, and at the specified maximum operating temperature. At the completion of the 96 hours each item shall be tested to determine conformance with requirements. In the event of any item failure during or after burn-in, the faulty item shall be repaired or replaced and the item resubjected to an additional 96-hour burn-in. Records of the burn-in testing, repairs and test results shall be maintained, and shall be available to the Buyer's representative upon request.

☐ 4.27 Welding Procedures: The Seller shall provide detailed procedures for each type of welding and each characteristically different welding joint to be used in the performance of this purchase order. These procedures shall be submitted to the Buyer for review and approval at least sixty (60) days prior to the use of such procedures on items fabricated for the Buyer. Revisions or changes to Buyer approved procedures must be submitted to the Buyer for review and approval prior to implementation.

☐ 4.28 Weld/Braze Inspection Report: A report(s) shall be submitted that indicates the complete inspection of welds or brazes from the initial fitup stage through the final inspection. Inspection reports shall be accompanied by all radiographic films, filler metal reports, etc. The reports shall contain the signature or stamp, and title of an authorized Seller representative.

☐ 4.29 Radiographic Quality Requirements: Items requiring radiographic inspection shall be radiographed and processed in accordance with Seller special process procedures that satisfy design specifications, standards or other purchase order requirements. Personnel reading and interpreting film shall have been subjected to examination and certification. Responsibility for this certification shall rest with the Seller, whether the Seller does the work or subcontracts to a specialized laboratory. Findings shall be reported on an appropriate form, including the name of the reader and the signature of a responsible representative. The radiographic film and a reproducible copy of the report shall accompany each shipment. An adequate method of identifying and cross referencing each film exposure, report, and item shall be provided. When parts are serialized, serial numbers shall appear on the report and the film.

☐ 4.30 Nondestructive Test Reports: All nondestructive testing shall be conducted in compliance with Seller special process procedures that satisfy the applicable provisions of the design specifications, or other purchase order requirements. Personnel and equipment utilized in performance of such tests shall have been evaluated and certified for the type of test performed.

Seller shall furnish with, or prior to, each shipment reports of such nondestructive examination of material or items furnished. These reports shall be identifiable to the respective item or material including the specific section, joints or views of the item furnished. These reports shall contain the signature and title of an authorized Seller representative. When items are serialized, the serial numbers shall appear on the reports.

☐ 4.31 Pressure or Leak Test Reports: Test reports shall be prepared for all pressure and leak tests. Such reports shall state the requirement, the Seller's test procedure number, and the observed result for each item, joint or connection tested. When items are serialized, the serial numbers shall appear on the report. The reports shall contain the signature and title of an authorized Seller representative, and shall accompany each shipment.

☐ 4.32 Cleaning Certification: Each shipment shall be accompanied by a certification which states that all Buyer requirements relative to cleaning and cleanliness have been completely satisfied. When items are serialized the serial numbers of the items included in the shipment shall appear in the certification. The certification shall reference the Seller's applicable cleaning procedure(s) identification number(s), and shall also contain the signature and title of an authorized Seller representative.

☐ 4.33 Calibration Certification: The Seller shall submit with each instrument/system a certification that the instrument/system has been calibrated and is ready for use. The certification shall contain, as a minimum, the identity of the instrument/system, the identification of the calibration procedure used, identification of the standards and/or equipment utilized for the calibration, and a statement that the calibration of the standards and/or equipment used is traceable to the National Bureau of Standards or some other recognized national standard. Detailed support data shall remain on file with the Seller and shall be available for review by the Buyer. The certification shall also contain the signature and title of an authorized Seller representative.

☐ 4.34 Operating-Maintenance Manual: Documentation containing operating procedures, maintenance instructions, spare parts lists, and handling procedures shall be submitted with the shipment of the first item.

☐ 4.35 Computer Software Configuration Management: The Seller shall develop and implement a software configuation management system that ensures an orderly development of software. The system shall establish requirements for placing software under configuration control, provide for the positive identification of software, and the control of all software baseline changes. The Seller shall submit a copy of his software configuration management procedure(s) with his proposal for review and evaluation.

☐ 4.36 Computer Software Design Control: The Seller shall develop written procedures describing the controls applied to the design of software, and the verification of the design through independent technical review. The procedures shall provide for documentation of review activities, including requirements for documenting comments and resolutions of comments. Seller software designs and review documentation shall be subject to review and approval by the Buyer.

☐ 4.37 Computer Software Verification Testing: The Seller shall test and verify computer software developed or modified to fulfill the requirements of the purchase order. The verification testing shall be accomplished by a comparison of test results with those from other verified software, or by a comparison with results from analytical solutions or Buyer approved alternatives.