NSTX-U SPECIFICATION FOR INNER PF1A COILS

Technical specification: NSTXU_1_1_3_3_3_SPEC_045

REVISION 4

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National Spherical Torus eXperiment Upgrade

NSTX-U
SPECIFICATION
FOR
INNER PF1A COILS

NSTXU_1_1_3_3_3_SPEC_045

NSTX-U-SPEC-MAG-006-R4

Work Planning #: 2254

DATED May 7, 2019

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NSTX-U SPECIFICATION

Record of Changes

Rev.	Date	Description of Changes
0	11/21/18	Initial Release
1	4/25/19	Added Helium Leak Check to Section 7.5
2	5/6/19	Corrected revision number in header
3	5/7/19	Corrected Footer
4	5/7/19	Corrected Revision Number; added DMS Number

NSTX-U SPECIFICATION

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1 INTRODUCTION & SCOPE

The National Spherical Torus eXperiment Upgrade (NSTX-U) is an experimental research facility funded by the U.S. Department of Energy (DOE) Fusion Energy Sciences (FES) that operates at the Princeton Plasma Physics Laboratory (PPPL). NSTX-U (http://nstx-u.pppl.gov/home). NSTX-U employs water-cooled copper electromagnetic coils to confine a hot plasma. During NSTX-U operation the coils are pulsed at high current (~ 10kA or more) for duration of 5 seconds, then cooled for a period of 20 minutes, then pulsed again. The Inner Poloidal Field (Inner PF) coils consist of 3 pairs of coils, namely PF1A, PF1B, and PF1C. The coils are installed symmetrically about the mid-plane of NSTX-U in Upper (U) and Lower (L) positions. The 6 coils are thus identified as PF1A-U, PF1A-L, PF1B-U, PF1B-L, PF1C-U, and PF1C-L.

During operation in 2016 a failure occurred in one of the Inner PF coils, and the NSTX-U project plans to replace all 6 coils as a result. The design of the coils has been modified to improve manufacturability. To ensure that the replacement coils are of the highest quality, prototype coils were fabricated in accordance with specification NSTX-U-SPEC-MAG-004-R3 to confirm the manufacturing process and to qualify suppliers. The prototype coil design served as proof of concept for the production coil design.

This specification covers the supply of Inner PF production coils. Only Subcontractors who have successfully completed the prototype supply and evaluation subcontract are qualified to supply the production coils. Note that successful execution of the prototype by a subcontractor does not guarantee that the option to proceed with the production coils will be exercised by PPPL with that or any other subcontractor.

Note also that the PF1A coils are nearly identical to the prototype PF1A-P coils such that the tooling used to fabricate the prototype coils may be adaptable to the production and spare coils.

Requirements are delineated in the following paragraphs. Subcontractor may elect to take exception and offer alternatives to any of these requirements in order to achieve a more cost effective or technically superior solution. Alternative Solutions that conform to standard practice are generally preferred. However, any exceptions taken, or alternatives offered to the requirements given in this specification shall be clearly noted and explained in the proposal. Any changes after award of the subcontract shall be mutually agreed and reflected in specification and subcontract revisions.

2 APPLICABLE DOCUMENTS

2.1 Standards and Codes

Materials and manufacturing/test methods used in fabrication of the equipment covered by this specification shall comply with the latest revision, in effect at date of issuance of this document, of the following currently approved applicable regulations, safety codes, specifications and standards, including applicable technical definitions as acknowledged and accepted in industry.

These Standards and Codes set forth the minimum requirements. The subcontractor is encouraged to recommend superior or more economical designs, processes, or materials.

ASTM American Society for Testing and Materials
ASTM B32- Standard Specification for Solder Material
ASTM B188-Standard Specification for Seamless Copper Bus Pipe and Tube
ASTM B170- Standard for Oxygen Free Electrolytic Copper Refinery Shapes

AWS American Welding Society
AWS A5.8 Classification: BCuP-5, Brazing Alloys

IEEE- Institute of Electrical and Electronic Engineers
IEEE #4, Techniques for Dielectric Tests

ASME E-499/E499M-11
Standard Practice for Leaks Using the Mass Spectrometer Leak Detector in the Detector Probe Mode

ASME E-498/E498M-11
Standard Practice for Leaks Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Tracer Probe Mode

NEMA LI 1-1998
Standards Publication for Industrial Laminating Thermosetting Products

3 APPLICABLE DRAWINGS

3.1 PPPL Drawings

Coil design drawings provided by PPPL are listed in Table 1. All dimensions refer to room temperature (20° C/ 68° F) conditions. Dimensional characteristics including tolerances and insulation builds are given on the drawings. For the PPPL-supplied G-11 fillers some geometry is only defined in the model using STP files, available upon request.

Table 1 – PF-1A Coil Fabrication Drawings

Drawing No.	Description	Revision
E-DC11102	PF-1A COIL ASSEMBLY	To be specified prior to subcontract signature
C-DC11175	PF COIL COOLANT FITTING DETAILS	To be specified prior to subcontract signature
B-DC11109	PF-1A COIL CONDUCTOR DETAIL	To be specified prior to subcontract signature

3.2 Subcontractor Drawings

Subcontractor shall prepare manufacturing and tooling drawings as required to complete fabrication. The manufacturing and tooling drawings shall be submitted to PPPL for review and approval prior to use. If the scope of supply includes the PF1A coils, then the manner in which the prototype tooling can be adapted to the production coils shall be explained and/or represented on revised drawings subject to PPPL review.

4 RESPONSIBILITIES

4.1 PPPL

PPPL will identify a point of contact, called the Princeton Technical Representative (PTR) for this procurement. The name of the PTR and contact information will be identified in the subcontract.

4.2 Subcontractor

The Subcontractor will provide the name and contact information for the project manager and technical point of contact for this procurement. The name of the Subcontractor point of contact shall be identified in the subcontract.

The Subcontractor shall participate in weekly meetings with PPPL and review the prior week's activities, outline the upcoming week's activities, and discuss any technical, quality, or management issues.

5 MATERIALS

5.1 PPPL-Supplied Materials

PPPL will supply the materials listed in the following sections. All PPPL-supplied material shall be inspected upon receipt and any discrepancies, deviations, or other defects shall be noted and communicated to PPPL as soon as possible. Receipt inspection of PPPL-supplied materials shall be documented and provided to PPPL. Materials may not be used prior to PPPL receiving the receipt inspection. Excess materials supplied by PPPL shall be returned to PPPL at the conclusion of the contract unless otherwise agreed by PPPL in writing. Insulation described in Section 5.1.3 shall be stored in an environment of 70% relative humidity or less.

5.1.1 Conductor

The conductor material will be C10200 oxygen-free, 100% IACS copper. Nominal dimensions and characteristics are given in Table 2.

Table 2 – Copper Conductor Characteristics

Coil	Height* (in)	Width* (in)	Hole Dia*. (in)	Coil conductor Length (ft)	Yield Strength (ksi ,0.2% elongation)
PF1A	0.481+/-.005	0.990 +/-.005	0.185	412	17 - 22

*Note: Dimensions in Table are provided for information only. Refer to the drawings listed in Appendix I for complete dimensions including tolerances.

The conductor for each coil will be supplied on spools in continuous length sufficient to wind the coil plus contingency for manufacturing. The conductor will be supplied by PPPL after pre-processing by grit blasting and priming.

The primer will be as follows.

Product name: CTD-450
Thickness: 0.0003 to 0.001 inch (0.007mm to 0.025mm)
Manufacturer: Composite Technology Development Inc.
2600 Campus Drive, Suite D
Lafayette, CO 80026
http://www.ctd-materials.com/contact-us
(303) 664-0394

Note: During winding with primed conductors, the mechanism used to maintain conductor tension cannot use a friction method that would damage the primer.

5.1.2 G-11 Filler Pieces, Plates and Lead Blocks

PPPL will supply NEMA G-11 filler pieces, plates, and lead blocks as indicated on the PPPL drawings. Trimming of these parts as necessary to wind the coil is allowed if determined necessary by the subcontractor. Any modifications made to these components for proper fit exceeding 1/8" of depth, must be approved, in writing, by PPPL prior to modification. All G-11 parts provided by PPPL are to be inspected prior to assembly for burrs or sharp edges and de-burred if necessary. Any de-burring shall be performed outside the clean room per section 7.1.1. The parts shall be cleaned with an appropriate solvent (see section 5.2.6) prior to use.

5.1.3 Insulation

As-built dimensions (after allowance for compression during winding) are given on the drawings. Materials are as follows:

S-2 Fiberglass Tape: (all heat cleaned and silane treated)
The 1" wide tape is .005" thick, Carolina Narrow Part Number: W113803
The 2" wide tape is .012" thick, Carolina Narrow Part Number: W1030405-2
The 5" wide tape is .012" thick, Carolina Narrow Part Number: W1030405-5
Kapton:
The ¾" wide Kapton tape is .0035" thick (Kapton is .002" thick and adhesive is .0015" thick), DuPont Kapton HN with Momentive 610 (cured silicon) adhesive
Co-Wound:
The Co-Wound tape is the 1" wide tape combined with the ¾" Kapton Tape. It is .0085" thick.

a) Turn-to-Turn Insulation

The Turn-to-Turn Insulation consists of two half-lapped layers of Co-Wound tape and one-half-lapped layer of 1” wide tape applied to each turn. The two half-lapped layers of Co-Wound tape shall be applied with the glass facing the conductor. The second half-lapped layer of the Co-Wound tape shall be staggered at 50% of the width with respect to the first half-lapped layer, with a tolerance of +.12”.

Note: PPPL defines the tolerance on a half-lapped layer (deviation of centerlines of over lapping layers from their ideal position) as +.12“/-.00”, to ensure there is always a minimum of a ½” of overlap with the possibility of exceeding the overlap by an additional .12 inches. Around bends this tolerance applies to the outer diameter while the inner diameter is allowed to exceed the additional .12” overlap as required by the radius. Excessive overlap should be avoided to ensure that the radial build of each layer (and the coil overall) is maintained.

b) Layer-to-Layer Insulation

The Layer-to-Layer Insulation consists of a single butt-lapped layer of 5” wide tape applied in addition to the insulation on the turns in adjacent layers. Other widths of glass with equivalent properties to the 4” and 5” wide tapes may be used with approval by PPPL.

c) Ground Insulation

The Ground Insulation consists of three features applied over the turn insulation winding pack.

1. Outer ground insulation applied over the outer diameter of the winding pack consisting of 7 half-lapped layers of 2” wide fiberglass tape.
2. Inner ground insulation applied over the inside diameter of the winding pack consisting of 7 half-lapped layers of 2” wide tape.
3. Top and bottom ground insulation consisting of 3 half-lapped layers of 2” wide tape applied between the winding pack and the G-11 plates.

The number of layers of ground wrap and/or the thickness of the ground wrap can be adjusted with PPPL approval if that is necessary to meet the required dimensional buildup as specified on the drawing. Alternative ground insulation glass widths with equivalent properties may be used with PPPL approval.

d) Glass Wrap for G-11 Filler Pieces

The Glass Wrap for G-11 Filler Pieces consists of 4 half-lapped layers of 1” wide tape. All of the G-11 Filler Pieces shall be completely wrapped on all surfaces in this manner. The G-11 Top and Bottom Plates shall be wrapped on three sides (the inner and outer diameters and also the surface that will be in the coil pack) in this manner. Reducing the

number of half-lapped layers for any G-11 part is permissible with prior approval from PPPL.

5.1.4 CTD 450 Primer

PPPL will supply primer to repair any damage to the primed conductor.

5.2 Subcontractor-Supplied Materials

Subcontractor will supply the equipment and materials listed in the following sections. A detailed list of all materials to be used in the deliverable scope under this specification shall be submitted to PPPL for review and approval prior to the start of materials procurement. Tooling that is developed specifically for fabricating the deliverable items of the subcontract shall be the property of PPPL and returned to PPPL at the conclusion of the contract unless otherwise agreed by PPPL in writing. Subcontractor shall provide SDS/MSDS's for all chemicals used throughout the fabrication process.

5.2.1 Tooling

All tooling, including the VPI mold, shall be supplied by the subcontractor. Subcontractor is also responsible for developing a removable winding mandrel. The design of tooling used for fabricating the deliverable items of the subcontract shall be reviewed and approved, in writing, by PPPL prior to use.

5.2.2 Coil Terminal Blocks

Machined blocks for coil terminals shall be fabricated from copper bar or plate per PPPL supplied drawings. Certified Material Test Reports (section 10.13.1) shall be provided for the materials used.

5.2.3 Braze Materials

Braze Material shall be Sil-Fos 15, a product of Handy & Harmon, Ltd, or PPPL-approved equivalent. No flux shall be used with the braze material. Characteristics shall be as follows:

Composition: 15% Ag, 80% Cu, 5% P
Melting Point: 1185° F (640° C)
Brazing Temperature Range: 1300F-1500F (704° C-816° C)

Certification of chemical composition of the Braze material shall be provided and along with documentation indicating compliance with AWS A5.8-2004, Classification BCuP-5. Alternative braze materials may be proposed and used only after approval by PPPL.

5.2.4 Void Materials

All regions within the winding volume not occupied by conductor or ground insulation shall be filled with certified (section 10.13.1) S-2 glass or G-11 fillers to minimize resin rich areas. When using S-2 glass to fill voids, the glass shall be densely applied to avoid resin rich areas. When using G-11 fillers, their edges shall be radiused (.020” to .039” radius) to prevent damage to adjacent insulation. Void areas where there is no glass, or G-11 filler shall not exceed 0.032” in any direction. G-11 fillers shall not contact other G-11 components without intermediate layer of glass insulation.

5.2.5 Insulating Resin

Insulating resin shall be as follows.

Product name: CTD-425

Manufacturer: Composite Technology Development, Inc. 2600 Campus Drive, Suite D Lafayette, C0 80026, (303) 664-0394
Description: Two-part system with Epoxy (EP) and Cyanate Ester (CE) catalyst in part A and Cyanate Ester (CE) in part B

5.2.6 Degreasing/Cleaning Solvents

All conductors, insulation blocks, and VPI mold parts shall be degreased/cleaned using a solvent that is able to dissolve grease, tar, wax, adhesives, oils and other soils, and is residue-free. Solvent selected by subcontractor requires PPPL approval prior to use. Recommend solvents are acetone and alcohol, however only alcohol is permitted for use on the primed copper.

5.2.7 Mold Release

Mold release material shall be proposed by subcontractor and approved, in writing, by PPPL prior to use.

5.2.8 Other Materials

All other materials not listed in section 5.1 or above as required to fabricate, test, and ship the deliverable items shall be supplied by the subcontractor. All insulating materials, including general-purpose kapton adhesive tape for joining and tailoring insulation, shall be of the same composition as the PPPL-supplied materials listed in 5.1.2 and 5.1.3. Additional insulating materials provided by the subcontractor shall be reviewed for approval by PPPL prior to purchase to verify compliance with this specification. All materials that become part of the coil must be certified (Section 10.13.1)

6 QUALITY ASSURANCE (QA) AND MANUFACTURING/INSPECTION/TEST (MIT) PLANS AND SAFETY

6.1 QA Plan

The subcontractor shall submit a Quality Assurance (QA) plan describing the specific quality assurance and quality control procedures and practices which will be implemented to meet the requirements of this specification; the plan shall include special process training and qualifications, oversight, and Quality organization participation in executing this specification. The plan shall include or reference detailed controls for the maintaining cleanliness (Section 7.1). The QA plan and any revisions require review and approval by PPPL prior to the start of design or manufacturing of the equipment under this specification.

6.2 MIT Plan

The Subcontractor shall submit a Manufacturing, Inspection and Test plan (MIT) for PPPL approval prior to the start of manufacture. The MIT must delineate the sequence of all processes and operations affecting quality, including in-process and final acceptance inspections and tests. The MIT shall identify parts; show their integrated flow into end items; identify critical manufacturing operations; and show inspections and the characteristics/dimensions to be inspected. The MIT shall include procedures for all processes that will occur including, but not limited to cleaning, taping, winding, VPI, soldering, brazing, inspections, and repairs. The MIT may include flow chart(s), Process Sheets, Shop Travelers, and inspection sheets, etc. Equipment to be used for all fabrication, inspections and tests shall be specified.

A traveler, whether integral to the MIT or a separate document, shall be used for data entry and operation sign-offs (operator, quality, and customer, as appropriate). Relevant data for inspections and tests shall include equipment ID and calibration status, acceptance values, actual values obtained, and pass/fail determination. PPPL will designate selected steps as mandatory "witness" points. Subcontractor shall notify PPPL a minimum of five (5) working days in advance of these witness points. Revisions or changes to the approved MIT or traveler shall be reviewed and approved, in writing, by PPPL prior to use.

Each individual (including engineers, technicians, QA, QC) who works directly with the MIT and/or related Traveler(s), interpreting instructions, entering data, or signing off on completion of steps, shall have documented training in the applicable document; both initial version and as revisions are issued. Those individuals approving the document(s) are considered to be trained.

6.3 Safety

The subcontractor shall provide a specific hazard analysis for PPPL resident oversight engineers and QA. PPPL employees will perform Job Hazard Analysis covering risks to themselves with the help of vendor employees. All applicable SDS/MSDS's must be available to PPPL employees for work performed in the areas that they are present.

7 FABRICATION

7.1 Cleanliness/Housekeeping

Cleanliness and housekeeping are an essential element to the success of the manufacturing of the Inner PF coils. The following steps shall be taken during the fabrication of the Inner PF Coils to enforce this practice.

7.1.1 Clean Environment

The final preparation of all insulating materials and fillers, the final preparation of the mold, the application of insulation, and the winding of the coil must be performed in a clean, humidity-controlled area that eliminates the risk of debris and dust particles such as metal chips, dirt, etc., from contaminating the coil insulation prior to VPI. Clean room atmosphere shall not exceed 70% relative humidity. The clean environment shall employ a positive pressure fan and a filter capable of capturing a particle size of 1 micron or smaller. If other activities that pose a risk of contamination are conducted in the same room, the work environment shall be enclosed, shall include an intermediate entry area with double doors in which workers can put on protective wear (section 7.1.3).

7.1.2 Step-Off Pads

Step-off pads shall be used at the entrances to the work areas to minimize transport of foreign particles and dirt into the work area. Step-off pads shall be changed at a minimum of once per day.

7.1.3 Gloves and Lab Coats

Latex, vinyl, rubber or cotton lint-free gloves, hair covers, and lab coats shall be worn in the work areas during the handling of insulated conductor, insulation, G-11 fillers or other components used in the construction of the Inner PF coils. An alternative glove material may be proposed, but needs to be approved, in writing, by PPPL prior to use. Lab coats and hair covers worn outside of the clean area, regardless of length of time, shall not be brought back into the clean area. No uncovered jewelry shall be permitted in the cleanroom. Eyeglasses when worn shall be inspected for loose screws and parts prior to entry into clean room.

7.1.4 Markers and Pencils

The use of lead pencils or non-approved markers is prohibited in the fabrication stations due to electrical tracking concerns. Marking on coil components shall be kept to a minimum, but when needed, only blue or black ink “Sharpie” brand name permanent markers may be used. The “Sharpie” product has been electrically tested by PPPL.

7.1.5 Conductive Contaminants

Filing, grinding, or any other operation that generates any kind of electrically conductive chips shall not be allowed in the clean area (section 7.1.1) without a PPPL-approved enclosure to contain such chips. Clamping and tooling design must preclude conductive debris from being generated. For example, any fixtures or clamps that could possibly abrade and form conductive chips are not allowed.

7.1.6 Material Protection

Material controls shall be addressed in the QA Plan (section 6.1) or MIT Plan (section 6.2). Copper conductor and all insulating materials shall be stored and processed in controlled areas free from metallic dust or other contaminants. All materials shall be protected from contamination by skin oil, etc. (see section 7.1.3). All materials shall be cleaned with approved degreaser (see section 5.2.6) using a lint-free cloth prior to entry into clean room. Once cleaned, the parts shall be protected to keep them clean, until ready for use. Tools shall be chosen so as to assure that they do no damage to the coil components (conductor, insulation, filler, etc.).

7.2 Conductor receipt, inspection and handling

7.2.1 Identification

The PPPL-assigned identification number shall be carried through on all documentation and references for traceability during processing.

7.2.2 Receipt Inspection

Upon arrival of each shipment of conductors the subcontractor shall inspect the shipment for any visible damage to the packaging and/or the conductor. Any discrepancies shall be immediately noted, photographed, documented on a Non-Conformance Report (NCR), and repaired in accordance with the PPPL-approved NCR disposition. Repairs should also be photographed. This receipt inspection step shall be delineated on the MIT plan. Receipt Inspection of PPPL-supplied materials shall be documented and provided to PPPL, prior to use. (See Section 5.1)

7.2.3 Conductor Handling

The conductor shall be fed into the winding line from the original shipping spools or transferred from the shipment spools to payout spools in such a way that it is not deformed in excess of its yield point and locally hardened. It shall not be re-spooled by unwinding and rewinding. When the conductor is transferred and when it is fed into the winding line it shall be inspected on all four sides and any surface defects shall be repaired. Additional primer will be supplied by PPPL (section 5.1.4) and a repair procedure for surface imperfections shall be proposed by the subcontractor to PPPL in the MIT Plan.

Immediately prior to application of the turn insulation, the conductor shall be wiped down with alcohol to remove excess oil, lubricant and grease. Sufficient time shall be allowed for the alcohol to fully evaporate before turn insulation is applied. The winding line tooling shall be inspected to ensure that no debris is created and deposited on the conductor surface after cleaning.

7.3 Key Winding Steps

Key steps of the winding sequence are described in this section. Subcontractor shall include all winding steps in the MIT and sub-tier procedures or travelers referenced by the MIT. Subcontractor shall have a minimum of two technicians working directly on the winding line whenever winding is in progress to assure there is attention to the conductor feed and insulation as well as the winding.

7.3.1 Winding Tooling and Initial Steps

Ensure that the winding tooling is cleaned, deburred and prepared for the commencement of winding.

Precautions such as clamping and pinning of G-11 Plates or Filler Pieces in place must also be taken to ensure the parts don’t shift during winding. Planning and measurement are required to ensure the proper shim thickness is used on the lead start side of the mandrel to ensure the full complement of turns fits in the prescribed coil space

7.3.2 Turn-to-Turn Insulation

The turn insulation shall be applied to the conductor using either an automated taping machine or manually by hand. An automated taping machine is strongly preferred so that precise control of dimensions is achieved. Joints at the end of one roll of insulation and the start of another shall be carefully tailored to retain the number of overlapping layers of glass and Kapton and to avoid excess build. See section 5.1.3 for Turn-to-Turn Insulation details. Insulation applied to G-11 Filler Pieces can be varied to between 2 and 4 half-lapped layers to achieve the correct positioning of the spacers in the coil body.

7.3.3 Dimensional Control

Apply sufficient tension on the conductor feed and a force normal to the conductor to achieve the nominal compression of the insulation while retaining dimensional tolerances on the gap between turns, the radial build, and the axial build of the winding pack, with minimal wandering of the conductor from its nominal spiral position. MIT plan shall propose method to monitor and maintain consistent tension values. To avoid over-compression of the insulation, tension beyond the nominal required to seat the conductor and maintain dimensional control is to be avoided. The dimensional build shall be monitored and recorded during winding. Any indication that the build of the turns cannot be held to the tolerance on the drawings shall be recorded as a non-conformance and communicated to PPPL before continuing with the winding process.

7.3.4 Start and Finish Leads

The turn insulation shall be continuous from inside the coil body up to 0.25” from the top of the G-11 Lead Block.

7.4 Handling of Coil Prior to VPI

Care shall be taken to avoid damage to the insulation. Damaged or contaminated insulation shall be photographed, documented in a non-conformance report, and replaced with new insulation in accordance with a repair procedure that is reviewed and approved, in writing, by PPPL before use.

7.5 Pre-VPI Cooling Passage Tests

Subcontractor shall propose method for pre-VPI leak check in vendor MIT. The water fitting adapter and connections shall have a leak rate no greater than 1x10 -9 standard cubic centimeters per second (sccs) air equivalent as measured by a Helium Mass Spectrometer Leak Detector (HMSLD). If water fittings are brazed on after the VPI is complete the cooling passage shall be leak checked after all fittings are assembled.

7.6 Pre-VPI Electrical Tests

Before VPI the dry coil shall be tested as indicated in the following sections. Ambient temperature and humidity shall be measured using calibrated instruments and recorded at the start of each electrical test. Test results shall be reviewed and approved, in writing, by PPPL before proceeding with VPI. Failed resistance tests shall be documented on nonconformance report.

7.6.1 DC resistance

DC resistance shall be measured and corrected for temperature as follows:

$$R_{20} = \frac{254.5 \times R_C}{234.5 + T_C}$$

Where:

R_c = measured resistance of the conductor (milliohms)
T_c = temperature of coil when resistance measurement is made (C°)

Measured resistance shall match nominal values given in Table 3 with tolerance of +0%/-3%. The nominal value is based on the average of the conductor min/max cross-sectional areas (as calculated from the allowable tolerances on the conductor), a nominal length, and a nominal copper conductivity. Adjustment to the nominal resistance to correct for the as-built length of the wound coil is permissible.

Table 3 – Nominal Coil DC Resistances at 20°C

Coil	Nominal Resistance (mΩ)
PF1A	7.70

7.6.2 AC Impedance

AC impedance and phase angle shall be scanned over the range of 10Hz to 200 kHz.

Impedance test device and test procedure shall be proposed by the subcontractor and approved, in writing, by PPPL.

7.6.3 Insulation Resistance

The insulation resistance shall be measured using a 500V DC Megger between the coil and a ground plane. The ground plane shall be made up of the mandrel, the flanges, and a tight fitting temporary conductive sheet. Coil terminals shall be jumpered together

and a voltage of 500V DC shall be applied for 60 seconds. Insulation resistance shall be recorded at the start and end of the 60 second test period and shall be equal to or greater than 10,000 Mega Ohms (at the end of the 60-second period).

Test procedure, including method to establish a ground plane, shall be proposed by the subcontractor and approved, in writing, by PPPL.

7.7 VPI Preparations

7.7.1 Mold Cleaning

The subcontractor shall thoroughly clean and degrease all surfaces of the mold prior to coil winding activities using the pre-approved solvent (refer to section 5.2.6).

7.7.2 Mold Leak Test

Prior to VPI, the subcontractor shall demonstrate and document that the VPI mold is capable of achieving the base pressure, leak and out-gassing rates, as specified in the PPPL-approved MIT/Traveler, from room temperature up to 100°C.

7.8 VPI and Curing

The VPI and curing process shall include the following steps. The detailed steps in the MIT plan will be subject to approval by PPPL. Deviation from the following requirements is only allowed with PPPL approval.

7.8.1 Leak Check and/or Rate of Rise Test

Leak check vacuum values to be approved, in writing, by PPPL

Full VPI system must be leak checked following a written plan including valves in open and closed positions with determination that valves do not leak when actuated

Leak check of molds to be performed at room temperature and 60C

7.8.2 Vacuum Pumping System

Shall include cold trap or other approved mechanism to prevent back streaming of fumes into vacuum mold

7.8.3 Resin Fill Volume Measurement

Recommend expanding a pressurized volume of nitrogen into the evacuated VPI mold and performing delta PV calculation).

7.8.4 Bake-out / de-gassing of the coil and resin delivery system before VPI.

De-gas by purging with nitrogen at 60C until a rate of rise check shows that there is diminishing return from further purging. Other methods may be used with PPPL approval.

7.8.5 Weighing, Mixing and De-gassing of the Resin

The weighing and measuring and mixing resin shall be carried out with precautions to guarantee cleanliness with method approved, in writing, by PPPL

Resin to be de-gassed reaching a pressure between 100 and 500 mTorr and with total de-gassing lasting a minimum of 6 hours. No bubbles should be present when raised to half the VPI fill pressure

7.8.6 Method to Document and Control Fill Rate

Fill level rate to be 2.0mm per minute or less

Soak time before curing to utilize entire 100 hours of CTD 425 resin working time barring extenuating circumstances such as leaks

Fill pressure should not be less than twice the de-gassing pressure

VPI fill lines must be clear so that they can be monitored during soaking to determine if the coil has stopped absorbing resin.

7.8.7 Optional Milking Process

Reverse flow under positive pressure after fill is complete until bubbles are gone.

7.8.8 Resin Use – Calculated versus Actual

Determine the quantity of resin that was used to impregnate the coil and comparison with expected fill volume based on fill volume measurement.

7.8.9 Oven Temperature Ramp Rates and Hold Times

Each step shall be annotated on the chart and MIT (beginning ramp up, end ramp up, etc.)

Differential temperature between lead stem and body of the coil shall not exceed 2º C until body of coil has passed 100ºC

From 90º C to 115º C the rate of rise in temperature shall not exceed 3º C per hour

Vendor must provide 24-hour coverage during curing cycle

Details of the VPI and curing process shall be delineated in the MIT plan which shall include provision for entry of key data and parameters as well as the recording of time and temperature throughout the VPI and curing process.

7.8.10 Resin Sample

For each coil, after the coil is removed from the mold, a small sample of excess cured resin is to be supplied to PPPL for analysis (10mm square by 2mm thick is adequate).

8 ACCEPTANCE TESTS and MEASUREMENTS

Test results that do not meet specified acceptance criteria shall be reported on a nonconformance report.

8.1 Dimensional Inspection

For measurements taken during the manufacturing process, using hand tools, the method shall be specified. Specifics to be included are how many points measured, which tools were used, the location of measurement taken, and whether the recorded value is an average or a conservative measurement.

Primary dimensional inspection of the completed coil shall be performed with a Coordinate Measuring Machine (CMM), Faro arm, Romer arm, or equivalent. The MIT plan shall delineate details of the inspection plan, including where and which instruments will be used.

For the measurement of the ID and the OD as a minimum the coil shall be measured at 8 locations evenly spaced around the circumference of the coil and 7 locations vertically along the inner and outer bore (112 total points).

An inspection report indicating all measured dimensions relative to their nominal value shall be generated. For the ID and OD, the data shall be evaluated to show that all of the requirements of the geometric tolerance are met including the cylindricity. Deviations beyond the tolerance shall be reported as a non-conformance.

8.2 Cooling Passage Tests

The purpose of these tests is to confirm the integrity of the cooling passages and fittings of each coil. Calibrated pressure gages shall be used. The water and copper temperature shall be recorded for each test.

8.2.1 Hydrostatic test

The coil shall be hydrostatically tested at 630 psi, using potable water. The hydrostatic pressure shall be 630 psi for 30 minutes with no drop in pressure after the system has

been isolated from the pressure supply. The pressure vs. time data shall be recorded every 5 minutes during the test. Resolution of the gauge shall be within 5 psi or better, with a range of between 800 and 1200 psi. The water shall be completely purged from the coil after testing by method described in MIT.

8.2.2 Water Flow Tests

The coil shall be tested for flow vs. pressure to verify that the cooling channel is clear. The pressure is to be measured directly at the inlet to the coil as well as at the coil outlet using calibrated pressure gauges. If the water is discharged directly to the room, the outlet pressure measurement is not required. The flow rate measurement may be made with a flow meter or by flowing water into a unit volume and timing it with a stop watch. This test shall be performed using potable water. Purge the system for 5 minutes before beginning the test to ensure all of the air is removed. Record inlet pressure, outlet pressure, temperature, and flow for each coil. Completely drain water from the coil at completion of the test. The measured flow shall match the values provided in Table 4 within +/- 10%. With approval by PPPL the test can be run at a lower pressure with the acceptance criteria scaled to match. The water shall be completely purged from the coil after testing by a method described in the MIT

Table 4 – Nominal Water Flow at 400 psi Pressure Drop

Coil	Nominal Flow (Gallons per minute)	Nominal Flow (Liters per minute)
PF1A	0.70	2.65

8.3 Electrical tests

Ambient temperature and humidity shall be measured using calibrated instruments and recorded at the start of each electrical test. Failed electrical tests shall be documented on nonconformance report.

8.3.1 DC resistance

The DC resistance measurement described in 7.6.1 shall be repeated.

8.3.2 AC impedance

The AC impedance and phase angle measurement of 7.6.2 shall be repeated.

Impedance test device and test procedure shall be proposed by the subcontractor and approved, in writing, by PPPL.

Results shall be reported to PPPL immediately following test. As records are obtained for identical coils, the AC impedance measurements shall be superimposed and compared. All measurements should be nearly identical for identical coils.

8.3.3 Insulation resistance

The insulation resistance measurement described in 7.6.3 shall be repeated. Test procedure, including method to establish a ground plane, shall be proposed by the subcontractor and approved, in writing, by PPPL.

8.3.4 Surge test

A surge test shall be performed using a capacitor discharge type surge tester. Characteristics of tester, test procedure, and pass/fail criteria, shall be reviewed and approved, in writing, by PPPL. PPPL may elect to furnish a suitable surge tester if subcontractor's tester is determined to be unsuitable.

Surges shall be applied at 1kV, 2kV, 3kV, 4kV and 5kV peak voltage. The decay of the voltage waveform of at each voltage level shall be superimposed and compared. All decay waveforms should be nearly identical.

As records are obtained for identical coils, the decay waveforms shall be superimposed and compared. All decay waveforms should be nearly identical for identical coils.

8.3.5 AC Impedance Test (repeat)

The AC impedance test described in 8.3.2 shall be repeated. Results shall be identical to the prior measurement.

8.3.6 DC Hipot Test

The coil shall be hipot tested between conductor pack and a ground plane. Coil terminals shall be jumpered together and the test voltage shall be raised at a rate not faster than 1kV per second and then applied for 60 seconds. Test voltages and leakage current shall be recorded during the test. No electrical breakdown shall occur.

Table 5 – Hipot Test Voltages

Coil	Test Voltage (kV)
PF1A	5

9 SPECIAL PROCESSES

9.1 Braze qualification program

The subcontractor shall qualify the braze procedure, equipment and operators prior to use. Braze qualification requirements are as follows.

9.1.1 Procedure

The subcontractor shall develop a braze procedure for performing the torch brazed lead terminals. Procedure shall be reviewed and approved, in writing, by PPPL prior to use. Care must be taken to ensure cleanliness of the clean area is not compromised by this activity, and the method for doing so shall be specified in the MIT plan.

9.1.2 Qualification of Procedure/Process

A minimum of three (3) successful (see section 9.1.4) braze samples shall be made to qualify the braze process and settings.

9.1.3 Qualification of Braze Operator

A minimum of three (3) successful braze samples shall be made by each braze operator to qualify his/her ability to perform successful braze (these may be the same samples used for procedure qualification). Braze samples shall be submitted to PPPL for inspection and approval.

9.1.4 Qualification Requirements

A visual inspection of the finished joint shall be made following braze clean-up to confirm complete flow of braze material into the joint area. The sample shall be cut in half and polished. The joint shall be free from all cracks and voids when viewed at 10x magnification. Qualification shall be documented along with samples provided to PPPL for their examination and concurrence before production brazing begins.

10 QUALITY ASSURANCE REQUIREMENTS

10.1 Inspection, Surveillance, and Audit

The subcontractor shall perform daily inspections and surveillance throughout the manufacturing of the coils as delineated in this specification. Such inspections and surveillances will be documented and available to PPPL.

PPPL reserves the right to designate selected manufacturing, inspection and/or test operations as mandatory Witness or Hold points. Subcontractor shall provide PPPL with notice five working days in advance of such points.

In addition, due to the critical nature of these components, authorized representatives of PPPL will be on-site on a regular basis to perform general inspection and surveillance. This PPPL on-site representative will serve as a liaison to resolve questions, inform PPPL of progress, and will have the authority to halt the fabrication process until issues are resolved. No work can occur without a PPPL representative present unless prior PPPL approval is given the specific work being done Winding will be considered a critical operation.

10.2 Subcontractor Quality Assurance Program

The subcontractor shall maintain an effective Quality Assurance (QA) Program to assure that the subcontractor's work meets the required level of quality and is performed in accordance with contractual requirements. Subcontractor's quality function shall be organized to have sufficient authority and independence to identify quality problems, verify conformance of supplied items or services to specified requirements and obtain satisfactory resolution of conflicts involving quality. Subcontractor's quality assurance function shall be actively involved in the planning; processing oversight, problem resolution, and determination of acceptability of all work under this technical specification and shall participate in the weekly meetings (section 4.2).

PPPL will conduct an on-site readiness review prior to start of fabrication. The scope of this review is to ensure all documentation (i.e. MIT and QA plan) is ready to be implemented and that the clean area and tooling are ready for the coil fabrication.

10.3 Submittal of Quality Assurance Program Description

The subcontractor shall submit with the proposal, one (1) copy of its Quality Assurance Program Manual, describing the Subcontractor's quality capability and general approach to quality assurance. The subcontractor shall also complete and submit at the time of proposal the PPPL PQA Supplier Quality Survey, which will be provided separately from this document. The manual and survey shall be subject to PPPL's review and acceptance prior to contract award.

10.4 Inspection and Test Procedures

Inspections and tests shall be performed in accordance with the MIT plan (section 6.2) with approved (separate or incorporated) procedures referencing criteria for acceptance or rejection. Adequate records shall be maintained and available for PPPL reviews.

10.5 Document Traceability and Records

The subcontractor shall maintain a system of documentation whereby objective evidence of required operations, inspections, examinations, and tests is systematically compiled, indexed and stored. Such objective evidence will include completed MIT plan (sections 6.2 and 10.7) and relevant data such as materials certifications, material test reports, inspection reports, discrepancy reports, etc. This information shall be complete, legible, validated by responsible personnel, and shall be traceable to subject items.

10.6 Equipment/Material Identification and Status

Material and equipment identification shall be maintained throughout the program and shall be traceable to the records. Status of acceptability shall be readily discernible through the use of tags, stamps, serial numbers or other positive means.

10.7 Manufacturing/Inspection/Test (MIT) Plan

The MIT Plan or referenced traveler shall be used as a signoff/approval document noting that critical manufacturing steps have been completed. Authorized personnel associated with the manufacturing, inspection and test processes shall initial and date the MIT Plan/traveler for this purpose. In addition, the MIT Plan/traveler is to provide witness points as well as references for test results, and measurements.

10.8 Witness/Hold Points and Notification of PPPL in Advance

PPPL reserves the right to designate selected manufacturing, inspection and/or test operations as mandatory Witness or Hold points. These default hold points apply, in addition to any others that may be added for this work:

- Satisfactory readiness review prior to start of coil processing (10.2).
- At the end of winding each coil layer, until measurements have been reviewed by PPPL.
- When welding / brazing qualifications are specified, welding / brazing must not occur until all required welding documentation is submitted and approved, in writing, by PPPL.
- Shipment must not be made until all document deliverables are collected and the shipping release form is signed and returned by PPPL (10.13.4).

10.9 Non-Conformance & Corrective Actions

Non-conforming items shall be positively identified, and, where possible, segregated to prevent use. The subcontractor shall document each non-conformance. PPPL's written approval is required prior to the use of any non-conforming item. The Subcontractor's system shall provide not only for timely resolution of non-conformances but also for analysis of non-conformances to determine the causes and to implement appropriate and effective corrective actions.

10.10 Calibration of Test and Measuring Equipment

Inspections and tests shall be performed using properly calibrated measuring and test equipment. Calibration standards shall be traceable to the National Institute for Standards and Technology (NIST) or equivalent. Where such standards do not exist, the basis used for calibration shall be documented. Test and measurement equipment identification numbers and last calibration date shall be recorded on corresponding steps of the MIT plan or procedures referenced by the MIT plan.

10.11 Performance and Documentation of Inspections and Tests

Each item to be delivered to PPPL shall be inspected and, where appropriate, tested by the Subcontractor to verify that they meet PPPL's requirements. Results shall be documented and reported to PPPL.

10.12 PPPL Receiving/Inspection

PPPL will perform Receiving Inspection on items or services supplied by Subcontractor, using either a sampling plan or 100% inspection. Discrepant items or services may be rejected and returned to Subcontractor or reworked by PPPL.

10.13 Process History

The subcontractor shall provide a Process History that includes a compilation of digital documents (in pdf, Microsoft Word, or Microsoft Excel format), detailing the objective evidence of the acceptability of the work performed. The Process History for each coil shall be provided to PPPL with the Shipping Release Request (See Appendix II). The Process History shall include as a minimum, but not be limited to the following:

10.13.1 Material Certifications

Manufacturer's Certified Material Test Reports (CMTRs) showing relevant chemical, mechanical and electrical properties of materials used, where applicable, shall be submitted to PPPL. Certifications for the insulation epoxy, copper material (lead blocks, etc.) braze material, and fillers are required as a minimum. It is recognized that only

certificates of grade may be available for materials such as fillers. Certifications shall be provided to PPPL when the subcontractor approves the material for use (start of job).

10.13.2 Inspection & Test Reports

The completed MIT plan, plus reports from all required inspections and tests shall provide the test or inspection parameters, actual results measured, identification and calibration status of the equipment used, and identification of the name the inspector/tester. Reports shall be reviewed by appropriate subcontractor personnel prior to submittal to PPPL.

10.13.3 Non-Conformance Reports

Signed copies of any non-conformance reports generated per section 10.9 shall be included in the process history.

10.13.4 Shipping Release

Subcontractor shall not ship (full or partial) without a "Product Quality Certification and Shipping Release" Form (Appendix II) signed by PPPL's Quality Assurance Representative. Subcontractor shall complete and sign the certification section, deliver the form to Princeton's Quality Assurance (QA) Representative, and hold shipment until the form is signed and returned. A copy of the fully executed form shall accompany each full or partial shipment.

10.14 Changes to PPPL Approved Documents

Revisions or changes by the Subcontractor to documents approved by PPPL and deviations from this specification shall be reviewed and approved in writing by PPPL prior to use.

10.15 Subcontractor's Responsibility for Conformance and Flow-down of Requirements to Sub-tier Suppliers

PPPL's review and/or approval of Subcontractor's documents nor PPPL's inspection of Subcontractor's items or services shall not relieve the Subcontractor of responsibility for full compliance with requirements of the purchase order/contract. The Subcontractor is responsible for assuring that all requirements and restrictions are imposed on any sub-tier suppliers.

11 SHIPPING STORAGE AND HANDLING

11.1 Preparation of Cooling Passages

Coolant passages will be dried and sealed for storage and subsequent shipment.

11.2 Coil Identifier

Each coil shall be affixed with a name tag that provides, as a minimum the coil identifier, subcontractor serial number, date the coil was completed, and coil weight in pounds.

11.3 Packing and Crating

Subcontractor is responsible for shipment to the PPPL site. Each coil shall be prepared for shipment is such a manner as to ensure acceptance by common carrier and to afford protection from normal hazards of transportation.

Packing and shipping details shall be submitted by subcontractor for review and approval by PPPL. Each coil shall be wrapped in minimum 0.005 inch (0.127 mm) thick polyethylene and crated for shipment. The crate shall be wooden and built for handling with slings from overhead cranes and forklifts. The crate shall protect the coil from shock, damage from load shift, and weather conditions, including precipitation. Shock sensors shall be added to the shipping crate. Characteristics of the shock sensors shall be provided with the packing and shipping details. Special care shall be taken to ensure that the lead area is adequately protected. Subcontractor name, customer name, purchase order number, coil identifier, and gross weight shall be marked on the shipping container. Photographs of the packed and crated items shall be submitted to PPPL prior to request for shipment

12 DELIVERABLES

12.1 Document deliverables

All documents shall be provided in digital (.pdf) format.

#	Deliverable Item	When Required	Specification Reference	Deliverable Received (✓)
1	QA Plan	Prior to the start of any work specific to the design and manufacturing scope under this specification, and after any revisions.	6.1	
2	Manufacturing and tooling drawings	Prior to use	3.2, 5.2.1	
3	List of subcontractor-supplied materials	Prior to procurement of materials and whenever list is revised	5.2	
4	Inspection reports of PPPL supplied material	Prior to use of material	5.1, 7.2.2	
5	Certified Material Test Reports for coil terminal blocks	Prior to use	5.2.2	
6	Certified Material Test Reports for additional coil lead and transition fillers	Prior to use	5.1.2	
7	Design of VPI mold and sealing features	Prior to use	5.2.1	
8	Manufacturing/Inspection /Test (MIT) plan, template	After receipt of order, for PPPL approval prior to the start of manufacture	6.2	
9	Procedures identified in the MIT	Prior to any manufacturing, inspection, or test activities specific to the scope of supply of this specification	6.2	
10	Protective measures in clean area during operation that could produce chips and filings	Prior to the work	7.1.5	
11	Non-conformance reports	Immediately following detection	7.3.3, 7.4, 10.9	
12	Non-conformance on dimensions	Immediately following detection	8.1, 10.9	
13	Procedure for repair of damaged insulation	Prior to use	7.4	

14	Pre-VPI coolant passage test results	Immediately following testing	7.5	
15	AC Impedance test procedure including description of tester	Prior to use	7.6.2, 8.3.2, 8.3.5	
16	Insulation Resistance test procedure including description of tester	Prior to use	7.6.3, 8.3.3	
17	Pre-VPI electrical test results	Immediately following testing	7.6	
18	Braze procedure	Prior to use	9.1.1	
19	Dimensional Inspection of completed coil	Prior to submittal of PPPL Shipping Release Form	8.1	
20	Surge test procedure including description of tester	Prior to use	8.3.4	
21	Hipot procedure including description of tester	Prior to use	8.3.6	
22	Packing and shipping details	Prior to use	11.3	
23	Manufacturing/Inspection /Test plan, filled out and signed off, per coil	After completion of all manufacturing, inspection, or test activities specific to the scope of supply of this specification	6.2	
24	Photographs of packed and crated items	Prior to submittal of PPPL Shipping Release Form	11.3	
25	Process history and PPPL Shipping Release Form	Prior to shipment of each coil	10.13	

12.2 Physical deliverables

#	Deliverable Item	When Required	Specification Reference	Deliverable Received (✓)
1	Braze Samples	Prior to brazing	9.1.2, 9.1.3	
2	Resin Sample	After VPI is completed	7.8.10	
3	Production coils	After completion and testing and preparation for shipment and approval of PPPL Shipping Release	10.13.4, 11	
		AFTER JOB COMPLETION		
4	Excess materials supplied by PPPL	After completion of all work scope	5.1	
5	Tooling procured or fabricated specifically for the scope of this specification	After completion of all work scope	5.2	

APPENDIX I

PPPL Shipping Release Form

PRINCETON UNIVERSITY PLASMA PHYSICS LABORATORY—PPPL
PRODUCT QUALITY CERTIFICATION & SHIPPING RELEASE

To be completed by supplier and submitted to PPPL with the Documentation package. Shipment (full or partial) is not authorized until PPPL returns this form signed.

Completed by Supplier

PPPL SUBCONTRACT/ ORDER #	ITEM #(s)	QUANTITY SHIPPED

ITEM DESCRIPTION	SUPPLIER REFERENCE #	SHIPMENT #

SUPPLIER'S CERTIFICATION

This is to certify that the products and services identified herein have been produced under a controlled quality assurance program and are in conformance with the procurement requirements including applicable codes, standards and specifications as identified in the above-referenced documents unless noted below. Any supporting documentation will be retained in accordance with the procurement requirements.

SIGNED: _____ DATE: _____

TITLE: _____ COMPANY: _____

Completed, signed, and returned by PPPL before shipment

PPPL (AUTHORIZED REPRESENTATIVE) SHIPPING RELEASE

This is to certify that evidence supporting the above Supplier's Certification statement has been reviewed and no product/service non-conformances from procurement requirements have been identified unless noted below. This product/service is hereby released for shipment.

This section serves as the Quality Assurance release for the above-described product for shipment. It does not constitute an acceptance thereof and does not relieve the Supplier, Manufacturer or Contractor of any and all responsibility or obligation imposed by the purchase contract. It does not waive any rights the Purchaser may have under the purchase contract, including the Purchaser's right to reject the above described material upon discovery of any deviations from requirements of the purchase contract, drawings and specifications.

NONCONFORMANCES FROM PROCUREMENT QUALITY REQUIREMENTS:

REMARKS/PRODUCT SERIAL NUMBERS:

BY PPPL QA REPRESENTATIVE (OR DESIGNEE)	DATE