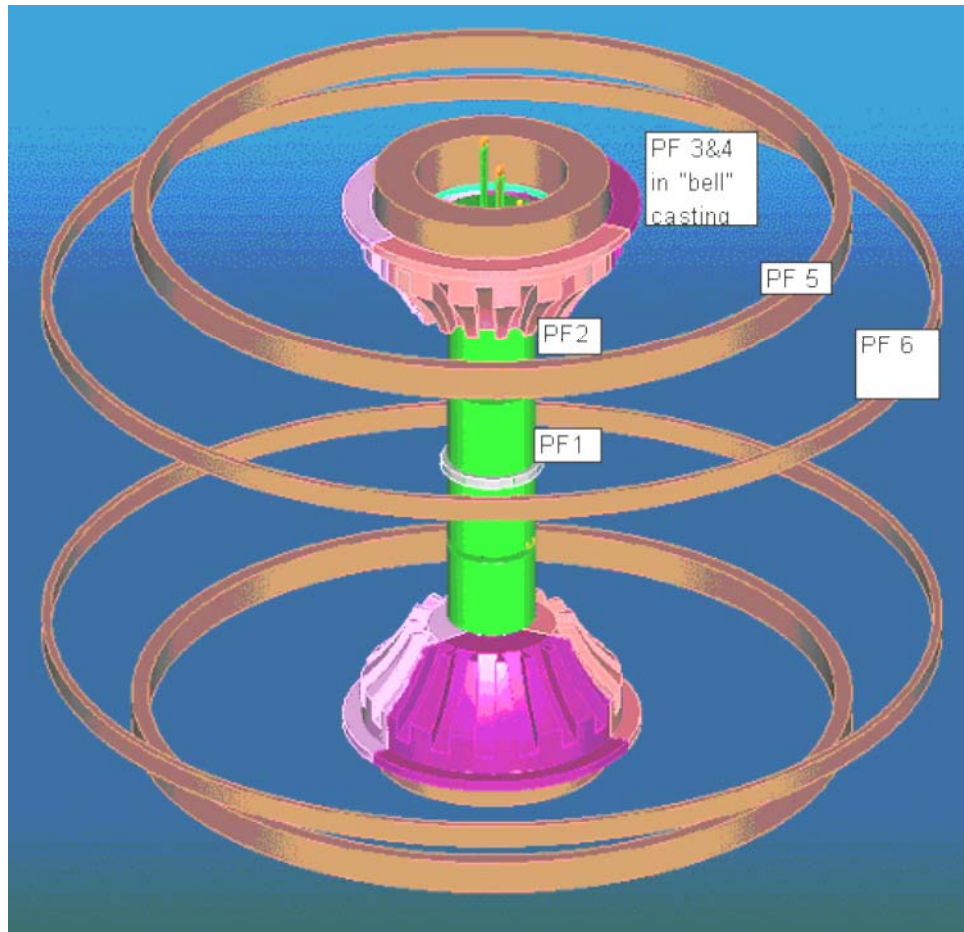


National Compact Stellarator Experiment (NCSX)

Draft Specification

FOR

**Conceptual Costing of the
NCSX Poloidal Field Coils**



DATED: April 23, 2002

**PRINCETON UNIVERSITY
PLASMA PHYSICS LABORATORY
(PPPL)
P.O. BOX 451
PRINCETON, N.J. 08543**

RECORD OF CHANGE

Revision	Date	TRB	Description of Change

1.0 INTRODUCTION AND SCOPE:

1.1 **INTRODUCTION:** this draft specification and attachments are to be the basis of a preconceptual level cost estimate for the Poloidal field coils of the NCSX device. *It is only meant to be used for that purpose.* This specification was adopted from those used for the recently constructed NSTX device in order to provide PPPL's standard quality assurance, general conditions, and reporting requirements. Since this material is only at the conceptual level, some inconsistencies and omissions are to be expected; in such cases, please call Phil Heitzenroeder at 609-243-3043, fax _3030, e-mail pheiten@pppl.gov or Tom Brown at 609-243-2156, fax _3030, e-mail tbrown@pppl.gov for clarification or guidance. Please document the basis of your estimate as fully as possible, including assumptions made. Costing is a major issue for NCSX; consequently, suggestions, which may reduce costs, are most welcome.

1.2 SCOPE:

- a. This specification defines the manufacturing requirements for the National Compact Stellarator Experiment (NCSX) Poloidal field (PF) coils. All of the PF coils are LN₂ inertially cooled (i.e., no active cooling during the pulse) copper coils. The PF system consists of an up-down symmetric set of six coils, for a total of (12) PF coils. Strict adherence to these specifications and the associated drawings is essential to ensure proper performance of the device and to minimize the risk of coil failure.
- b. Subcontractor shall furnish all material, labor and facilities necessary to complete the work as defined in the contract documents subject to the qualifications, conditions, or exceptions noted herein.

2.0 APPLICABLE DOCUMENTS:

2.1 DRAWINGS

- a. PPPL will supply basic top, side, and cross-sectional view drawings for each coil. Vendor is to supply all other process related and detail drawings.)
- b. Dimensions in drawings and specifications refer to conditions at room temperature (20° C/ 68° F).

2.2 STANDARDS AND CODES:

- a. 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 purchase order, of the following currently approved applicable regulations,

safety codes, specifications and standards, including applicable technical definitions as acknowledged and accepted in industry.

ASTM American Society for Testing and Materials

CDA Copper Development Association

CDA Standards Handbook, Part 2 (Wrought Products) Alloy Data, CDA Alloy No. 10200 or 10700

Conductor:

The conductor sizes used were selected from Outokumpu's brochure: "Hollow Copper Conductors for Magnet Windings" but can be procured from other sources. Copper alloy CDA-10200 or 10700 (OFHC copper with silver) shall be used to minimize the heat affected braze zones.

IEEE- Institute of Electrical and Electronic Engineers

IEEE #4, Techniques for Dielectric Tests\

NEMA-National Electrical Manufacturers Association

Grades and specifications for materials developed for the electric and electronics industries.

- b. The above Standards and Codes set forth the minimum requirements. They may be exceeded by Subcontractor with written permission from PPPL, if in Subcontractor's judgment, superior or more economical designs or materials are available for successful and continuous operations, as required by the specification.

2.3 GENERAL STATEMENT

Subcontractor agrees, represents and warrants that all services, designs, equipment and material sold or otherwise provided to PPPL by Subcontractor comply with applicable, Federal, State and Local laws, regulations and codes, and all applicable specifications and standards including those specified above, in each case as in effect at the date of order placement. Subcontractor shall provide PPPL with a Certificate of Compliance identifying the codes, standards and regulations complied with, and any exceptions taken, in the design and fabrication of deliverable items.

3.0 REQUIREMENTS:

3.1 EQUIPMENT DEFINITION

3.1.1 General Design Features

- a. Dimensional and physical characteristics of the coils are summarized in Table 3.1.1-1.
- b. Tolerance requirements are listed below. Strict adherence to these dimensions is critical to the assembly and performance of the subject equipment.

Radial current position of the coil centroid: +/- 2mm
 Vertical current position of the coil centroid: +/- 1mm.

Table 3.1.1-1. NCSX PF Coil Dimensional and Physical Characteristics

(Note: 2 of each coil are required.)

Parameter	Units	PF-1	PF-2	PF-3	PF-4	PF-5	PF-6
Max. Total current	MA-turns	1.34	1.63	2.35	1.9	0.19	0.09
radius	m	0.22	0.22	0.27	0.59	2.13	2.70
height, Z	m	0.23	0.68	1.24	1.58	1.47	0.97
bundle dr	mm	101.43	101.43	200.57	250.15	101.43	51.86
bundle dz	mm	402.38	402.96	402.38	288.29	174.19	117.11
gross cur. dens.	A/mm ²	32.83	39.88	29.12	26.35	10.75	14.82
total turns	#	56.00	68.00	112.00	100.00	24.00	8.00
turns high	#	14	17	14	10	6	4
turns wide	#	4	4	8	10	4	2
current per turn	A	23928.57	23970.59	20982.14	19000.00	7916.67	11250.00
packing fraction		0.75	0.75	0.75	0.75	0.75	0.75
length per turn	m	1.38	1.38	1.70	3.71	13.38	16.96
total length of cu per coil	m	77.41	94.00	190.00	370.71	321.20	135.72
turn height	mm	27.00	22.00	27.00	27.00	27.00	27.00
turn width	mm	22.50	22.50	22.50	22.50	22.50	22.50
coolant hole dia.	mm	13.50	13.50	13.50	13.50	13.50	13.50
copper corner radii	mm	2.50	2.50	2.50	2.50	2.50	2.50
conductor area	mm ²	459.00	346.50	459.00	459.00	459.00	459.00
Initial resistance of coil	ohms	5.20E-07	8.37E-07	1.28E-06	2.49E-06	2.16E-06	9.12E-07
calculated coil wt.	kg	304.85	279.45	748.27	1459.92	1264.93	534.48

- 3.1.2 Materials: Vendor is to procure and / or supply all materials required for fabrication of the coils.

3.1.2.1 Copper Conductor: The dimensions for the copper conductors details are listed in Table 3.1.1-1.

3.1.2.2 Insulation System: All of the PF coils will be insulated with "S" glass and vacuum-pressure impregnated with epoxy resin suitable for the operational environment of the coils. Vendor is to specify all details of the insulation, resin, and processing, subject to review and approval by

Table 3.1.2.2-1. PF Coil Insulation Requirements

Turn to turn insulation:	2 layers 0.19 mm "S" glass, half lapped.
Layer to layer insulation:	1 layer 0.75 mm "S" glass.
Ground wrap insulation:	2 layers 0.38 mm "S" glass, half lapped.

PPPL: The coils will be pre-cooled to 77 K prior to a shot; the maximum coil temperature at the end of a shot is ~110 K. Details of the insulation for the PF coils are given in Table 3.2.2.2-1.

3.1.2.3 Ground Plane

A dielectric ground plane shall be applied to the surface of the cured coils. Conducting Varnish #8003, thermal class F (155°C) shall be used as the dielectric overcoat material (Insulating Materials Incorp.). An equivalent product may be used with prior approval by PPPL.

3.1.2.4 Degreasing/Cleaning Solvent:

All conductors shall be degreased/cleaned using a solvent which has been pre-approved by PPPL. This solvent must be able to dissolve grease, tar, wax, adhesives, oils and other soils, and must be residue free.

3.1.2.5 Joints:

- a. Coil joints to be made by induction brazing using "Sil-Fos" braze alloy. Vendor must develop processing details and a technician qualification program.

3.1.2.6 Fillers:

All lead or joggle fillers shall be made of NEMA Grade G-11 glass reinforced epoxy meeting all NEMA (National Electrical Manufacturers Association) "G-11" Grade specifications.

3.1.2.7 Machined Coil Lead Blocks and Electrical Flags:

Machined blocks for coil leads shall be fabricated from copper bar or plate. Alloy shall be CDA alloy no.10200 or 10400 oxygen free copper having a minimum yield strength of 30,000 psi (0.5% elong.) or PPPL approved equivalent.

3.2 **COIL FABRICATION:**

This section describes a recommended procedure for fabricating the subject equipment. The Subcontractor shall submit for approval by PPPL, a Manufacturing, Inspection, and Test (MIT) plan. No deviations from the MIT plan will be accepted without PPPL approval.

3.2.2 Conductor Cleaning:

The copper conductors) shall be removed from their containers, cleaned and inspected. The external surfaces of the conductor must be cleaned with an approved residue free solvent. The visible surfaces of the copper spool shall be clean and free of slivers, burrs, scale and other injurious defects.

3.2.3 Material Protection:

Cleaned copper, whether bare or insulated, shall be stored and processed in an environment free from metallic dust or other contaminants. The copper surface and insulating materials shall be protected from skin oil, etc., by requiring shop personnel to handle conductors only while wearing clean, lint free, white cotton gloves. Insulation and in-process subassemblies shall be processed and stored in controlled clean areas.

3.2.4 Conductor Inspection:

The conductors shall then be moved to an inspection station where they will be inspected per requirements in Section 4.0 paragraph 4.1.

3.2.6 Conductor Preparation:

The copper conductor spools shall be mounted onto support stands to allow the copper conductor to be fed freely onto the winding mandrel. The conductor must be pre-cleaned to assure that it is not contaminated with oil or grease remaining from the extrusion process.

3.2.7 Coil Assembly

- a. The winding station shall include a coil-winding unit; tension units; copper spool stations; conductor sandblast units; portable insulation taping machines; brazing units; pre-bend rollers and miscellaneous tools and equipment.

Note: All tooling and fixturing necessary to complete the winding operation, is the responsibility of the Subcontractor.

- d. Winding Tension:

The magnitude of the tension and method for monitoring tension value shall be pre-determined and tension details to be approved by PPPL.

3.2.8 Layer to Layer Coil Joints:

The detail and location of these joints are shown in the coil drawings identified in Appendix I. ***Field errors are a critical issue for NCSX; the joint details must be precisely adhered to.***

3.2.8.1 Joint Preparation:

- b. The ends of each conductor shall be machined with a ferrule to ensure a leak-tight coolant passage. Sil-Fos rings are to be pre-positioned at the ends of the ferrule. A foil of Sil-Fos is to be placed at the joint interface, and a "hairpin" of formed "Sil-Fos" wire is to be placed adjacent to the foil on the outer surface to provide additional braze alloy. The conductor is to be induction heated and monitored with an infrared feedback control system. Details of the brazing system and process are to be reviewed and approved by PPPL.
- c. The conductors shall be pre-formed to proper layer radius prior to joining.
- d. The ends of the conductors shall be properly cleaned prior to brazing.
- e. Prior to joining coil layers an insulation resistance and ultrasonic joint test shall be performed (see section 4.2.1).

3.2.8.2 Conductor Joining Prerequisites

- a. Silver brazing using "Sil-Fos" or equivalent is required for fabricating all conductor joints. No additional flux is to be used. These procedures shall be reviewed and approved by PPPL.

- b. The Subcontractor's brazing technician must be qualified and demonstrate his ability to perform the operations with skill and efficiency.
 - 1. The technician must fabricate a minimum of three sample joints, which shall then be tested to verify their mechanical integrity. These tests must be successfully completed prior to the operator becoming qualified; it is required that conductor failure occur outside the joined region.
- c. Vendor to propose a helium leak testing method for all joints to verify joint integrity. Procedure to be reviewed and approved by PPPL prior to use.

3.2.9 Lead Area Turn Insulation:

Turn insulation shall be tailored to fit neatly electrical terminals.

3.2.10 Coil Leads:

The coil conductor leads shall be formed per approved PPPL drawings .

3.2.11 Electrical Connections:

The copper electrical connections shall be silver brazed with "Sil-Fos" to the conductor ends during the winding process. Joining materials are specified in section 3.1.2.5. Braze process must be PPPL approved.

3.2.12 Coil Fillers; ground wrap.

- a. All filler blocks shall be made with NEMA Grade G-11 glass reinforced epoxy which has been sanded and vacuum cleaned.
- b. The ground insulation detailed in Sect. 3.1.2.2 shall be applied half lapped on the ID of the coil.

3.2.13 Coil Vacuum Pressure Impregnation

- a. Vendor to design and supply the closed vacuum pressure impregnation mold and all required equipment. Alternatively, an autoclave vacuum pressure impregnation process may be used.
- b. Vendor is to specify the epoxy resin system to be used. The choice of resin and details of the VPI process are subject to PPPL's review and approval. ***This is a critical process, which requires particular attention to process control.***

3.2.14 Outer Ground Wall Insulation:

- a. The outer ground wall insulation shall be applied to the outside diameter of coil using half-lapped layers of glass tape.
- b. All layers of ground insulation shall be applied in the same direction.
- c. The ground insulation shall be tailored to fit neatly around the conductor end electrical flags.

3.2.16 Surface Evaluation

Subcontractor shall evaluate the machined coil bundle surfaces to verify freedom from defects such as cracks, dry spots, voids, etc. The coil bundle surfaces shall not be patched or mechanically processed without written approval of PPPL. There shall be no voids or delaminations. Surface cracks shall be reviewed with PPPL for disposition.

3.2.17 Evaluation of Finished Surfaces

The cured coils shall be checked for dimensional conformance with the drawings.

3.2.18 Ground Plane:

After the cured coil has been inspected, the outer surfaces of the coils shall be painted with a conductive paint to provide a ground plane on the outer wall of the coil insulation.

4.0 TEST REQUIREMENTS:

Mechanical and electrical inspections and tests shall be performed on each coil. Reports of required tests are to be provided to PPPL for acceptance in accordance with manufacturers inspection and test (MIT) plan, approved by PPPL. Seller shall notify PPPL in advance to permit PPPL's representatives to witness any of the inspections or tests, either in-process or final acceptance.

4.1 **RECEIVING INSPECTION- CONDUCTOR**

4.1.1 Dimensional Measurements/Inspections

Conductors shall be checked to verify that the cross-sectional dimensions are within the required tolerance. They will also be inspected for surface conditions.

4.2 IN-PROCESS TESTING

4.2.1 Insulation Resistance Test Prior To Joint

An insulation resistance test shall be performed of each wound conductor prior to making up the layer to layer joint. The insulation resistance shall be verified by applying a 500 Volt Megger to the layer be tested with the adjacent conductors grounded. Hold at 500 V until there is no change in resistance. The insulation resistance shall be greater than 1000 M Ω

4.2.3 Tests After Assembly and Prior to Oven Cure:

a. DC Resistance:

Measure and record the dc resistance and temperature of each coil and lead. The resistance shall agree with the calculated value (supplied by PPPL) within 3.0%.

b. Insulation Resistance to Ground

The insulation resistance shall be verified by applying a 500 V Megger between the coil and the ground plane. Hold at 500 V until there is no change in resistance. The insulation resistance shall be greater than 1000 M Ω .

4.3 FINAL ACCEPTANCE TESTS

These tests and inspections shall be performed once the coils are in a deliverable configuration.

4.3.1 Inspection:

A careful visual inspection and dimensional check shall be made according to applicable drawings.

4.3.3 Final Electrical Tests:

If any of the following electrical tests show evidence of disruptive discharges indicating insulation failure or weakness, (i.e., excessive current leakage, flashover), this shall be cause for rejection. It is the Seller's responsibility to insure that the specified test voltage levels are not exceeded, and that proper testing safeguards are taken to prevent test equipment and circuitry malfunctions which could result in over-voltage and/or switching transients.

a. DC Resistance:

Measure and record the dc resistance and temperature of the coil. The resistance shall agree with calculated coil resistances within 10.0%.

b. Insulation Resistance to Ground

The insulation resistance of the coil shall be verified by applying a 5 kV Megger between the coil and the ground plane. The insulation resistance shall be greater than 1000 MΩ. (Perform prior to 13 kV Hipot test.)

c. DC Hipot Tests

The insulation between the coil bundle and ground shall be verified by applying a 13 kV DC Hipot between all turns (start and finish leads jumpered together) and ground. Voltage shall be ramped up in 30 seconds, held for 60 seconds, and ramped down in 30 seconds. Leakage current shall be recorded during ramp up and down, and once every 10 seconds during the 60 second interval. Leakage current shall not exceed 10 μ Amps.

5.0 QUALITY ASSURANCE REQUIREMENTS

5.1 INSPECTION/ SURVEILLANCE/AUDIT BY PRINCETON

Authorized representatives of PPPL and the U. S. Government shall have the right at all reasonable times to visit the Subcontractor's premises and those of Subcontractor's suppliers during the performance of the procurement for the purposes of inspection, surveillance, audit and/or obtaining any required information as may be necessary to assure that items or services are being furnished in accordance with specified requirements. Such visits shall be coordinated with the Subcontractor's personnel to minimize interference with the normal operations of said premises. The Subcontractor shall make available records and documentation necessary for this function and shall provide all reasonable facilities and assistance for the safety and convenience of PPPL and/or U. S. Government representatives in the performance of their duties. PPPL and the U. S. Government recognize the Subcontractor's right to withhold information concerning proprietary processes. The Subcontractor agrees to insert the paragraph above in each lower tier procurement issued hereunder.

5.2 SUBCONTRACTOR'S RESPONSIBILITY FOR CONFORMANCE

Neither PPPL's review and/or approval of Subcontractor's documents nor PPPL's inspection of Subcontractor's items or services shall relieve the Subcontractor of responsibility for full compliance with requirements of the purchase order/contract.

5.3 QUALITY ASSURANCE PLAN

Subcontractor shall submit as soon as practical after the subcontract/purchase order award, two (2) copies of its Quality Assurance Plan, describing the specific quality assurance and quality control procedures and practices to meet the requirements of this particular subcontract/purchase order, for PPPL review and approval.

5.4 MANUFACTURING, INSPECTION AND TEST PLAN (MIT)

Subcontractor shall prepare and submit for PPPL review and approval a Manufacturing/Inspection/Test Plan which identifies parts, sub-assemblies, etc.; shows their integrated flow into end items; and identifies critical manufacturing operations as well as inspections and tests. Preparing the Plan may include developing a flow chart and generating Process Sheets/Shop Travelers, etc. PPPL may designate selected manufacturing, inspection and/or test operations as mandatory "witness" points based on the MIT plan. Subcontractor shall provide PPPL with five (5) working days notice in advance of such witness points.

5.5 INSPECTION AND TEST PROCEDURES

Inspections and tests shall be performed in accordance with written procedures referencing criteria for acceptance or rejection. Adequate records shall be maintained and available for PPPL's review.

5.6 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 may include "travelers"; and material test, certification, inspection, examination, test and discrepancy reports; which shall be complete, legible, and validated by responsible personnel and shall be traceable to subject items.

5.7 EQUIPMENT/MATERIAL IDENTIFICATION AND STATUS

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

5.8 **DOCUMENT REVIEW, APPROVAL AND CONTROL**

The Subcontractor shall provide a system for distribution and control of approved documents and changes thereto. The system shall use procedures which provide for review and approval of design documents (drawings, specifications, etc.), prior to issuance for use, and for approval and incorporation of changes in a formal and orderly manner. The system shall control obsolete documents to prevent inadvertent use.

5.9 **CALIBRATION OF TEST AND MEASURING EQUIPMENT**

Inspections and tests shall be performed using properly calibrated measuring and test equipment. Subcontractor shall have in its possession the necessary equipment to perform the required inspections and tests. Calibration standards shall be traceable to the National Institute for Standards and Technology (NIST) or equivalent. Subcontractor shall impose these calibration requirements on sub tier suppliers.

5.10 **RELEASE FOR SHIPMENT FORM**

Subcontractor shall have a signed "Product Quality Certification and Shipping Release" Form to be provided by PPPL's Quality Assurance Representative prior to PPPL acceptance of procured items or services for full or partial shipment. PPPL reserves the right to refuse to accept shipments unless accompanied by a signed "Shipping Release" Form .

5.11 **PROCESS HISTORY**

Subcontractor shall provide to PPPL a Process History which includes a compilation of documents, detailing the objective evidence of the acceptability of the work performed. The Process History shall include as a minimum, but not be limited to, the following:

5.11.1 Certificate Of Compliance (C of C)

Subcontractor's C of C, stating that the work performed conforms in every respect to the physical configuration and functional inspection/test requirements. The C of C shall be signed by Subcontractor's Quality Assurance (QA) Manager.

5.11.2 Material Certifications

The Subcontractor shall submit copies of inspection reports, test data, and/or certifications from vendors, showing relevant chemical, mechanical and electrical properties of materials used, where applicable, as well as documents showing adherence to in-process requirements. Material certifications from sub-tier suppliers shall also be submitted.

5.11.3 Inspection/Test Documents

Copies of filled in and completed process planning and control documents (travelers, etc.) which verify controlled execution of the required work. (Records shall be available for review but may not be required for delivery.)

5.11.4 Inspection Reports

Copies of the original reports of all required inspections and examinations, properly validated by authorized personnel.

5.11.5 Test Reports

Copies of the original test data sheets or reports of all required tests, both in-process and acceptance, properly validated by authorized personnel.

5.11.6 Fabrication Drawings

Copies of final fabrication drawings including all approved changes made during fabrication.

5.12 **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 will be rejected and returned to Subcontractor or reworked by PPPL. Costs caused by rejects will be charged to Subcontractor.

6.0 DOCUMENTATION REQUIREMENTS

6.1 PROPOSAL TECHNICAL DOCUMENTATION

- a. Subcontractor shall submit as part of his proposal documentation in preliminary or outline form, the QA Plan (refer to section 5.3), the Manufacturing/Inspection/Test Plan (refer to section 5.4), and procedures for tests (refer to section 5.5).
- b. Subcontractor shall submit as part of the proposal a preliminary description of the press mold, tension tube support fixture and winding setup (refer to sections 3.2.5, 3.2.6, 3.2.7 and 3.2.13).

6.2 DOCUMENTATION AFTER CONTRACT AWARD AND PRIOR TO FABRICATION

- a. Subcontractor shall submit (2 copies) final versions of the QA Plan (refer to section 5.3), the Manufacturing/Inspection/Test Plan (refer to section 5.4), and procedures for tests (refer to section 5.5) for PPPL review and approval within 30 days of contract award.
- b. Subcontractor shall submit (2 copies) a final description of the press mold, tension tube support fixture and winding setup (refer to sections 3.2.5, 3.2.6, 3.2.7 and 3.2.13) for PPPL review and approval within 30 days of contract award.
- c. Subcontractor shall submit (2 copies) of final fabrication drawings for PPPL review and approval within 30 days of contract award.

6.3 DOCUMENTATION PRIOR TO SHIPMENT

- a. Subcontractor shall submit (2 copies) all documents identified in section 5.11, Process History.
- b. Subcontractor shall submit an inventory of excess materials provided by PPPL.

7.0 SHIPPING STORAGE AND HANDLING

- a. The conductor coolant tubes shall be drained of all water and sealed for storage and subsequent shipment.
- b. The each shall be crated for shipment. The crate shall be built for moving on rollers, handling with slings from overhead cranes and forklifts.
- c. The crate shall protect the coil from shock and weather conditions, including precipitation and protection against freezing. Subcontractor's name, shipper, purchase order number, contents and gross weight shall be marked on the

shipping container. Subcontractor is responsible arranging shipment, and for the safe arrival of the coils at PPPL in Princeton , New Jersey, USA.

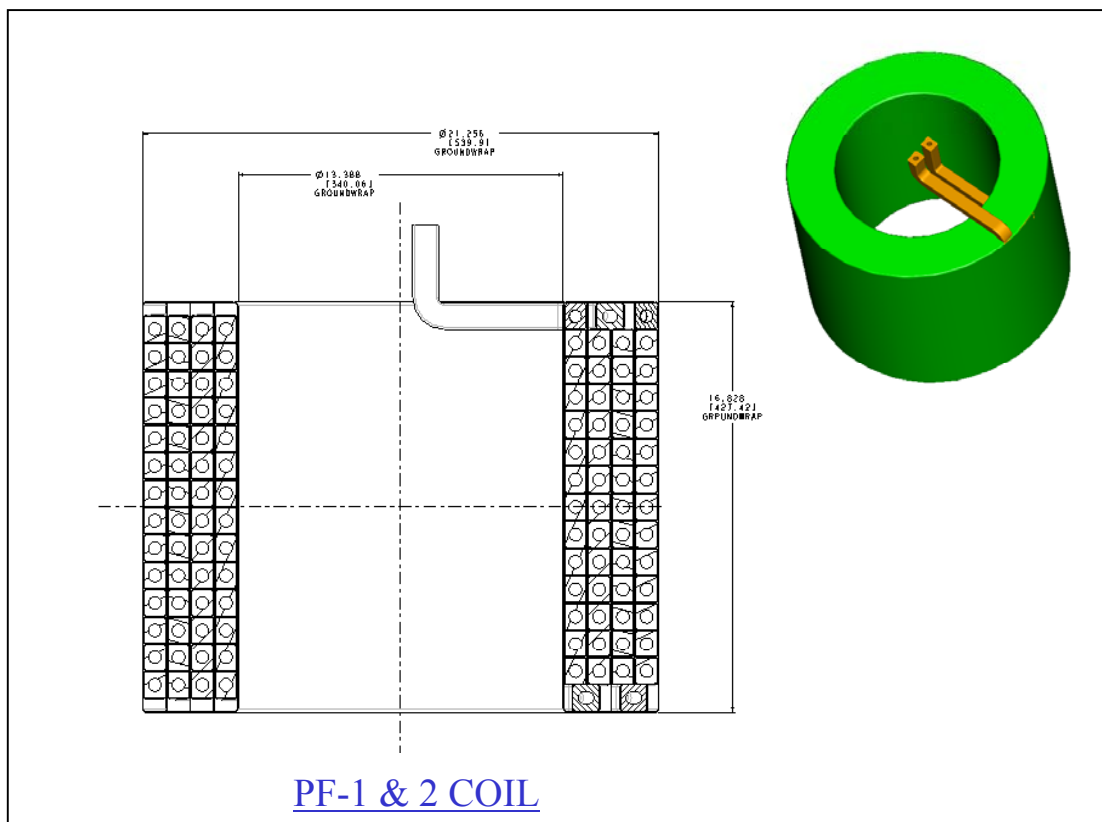
- d. The coil shall be prepared for shipment in such a manner as to ensure acceptance by common carrier for transportation at the lowest applicable rate and to afford protection from normal hazards of transportation.

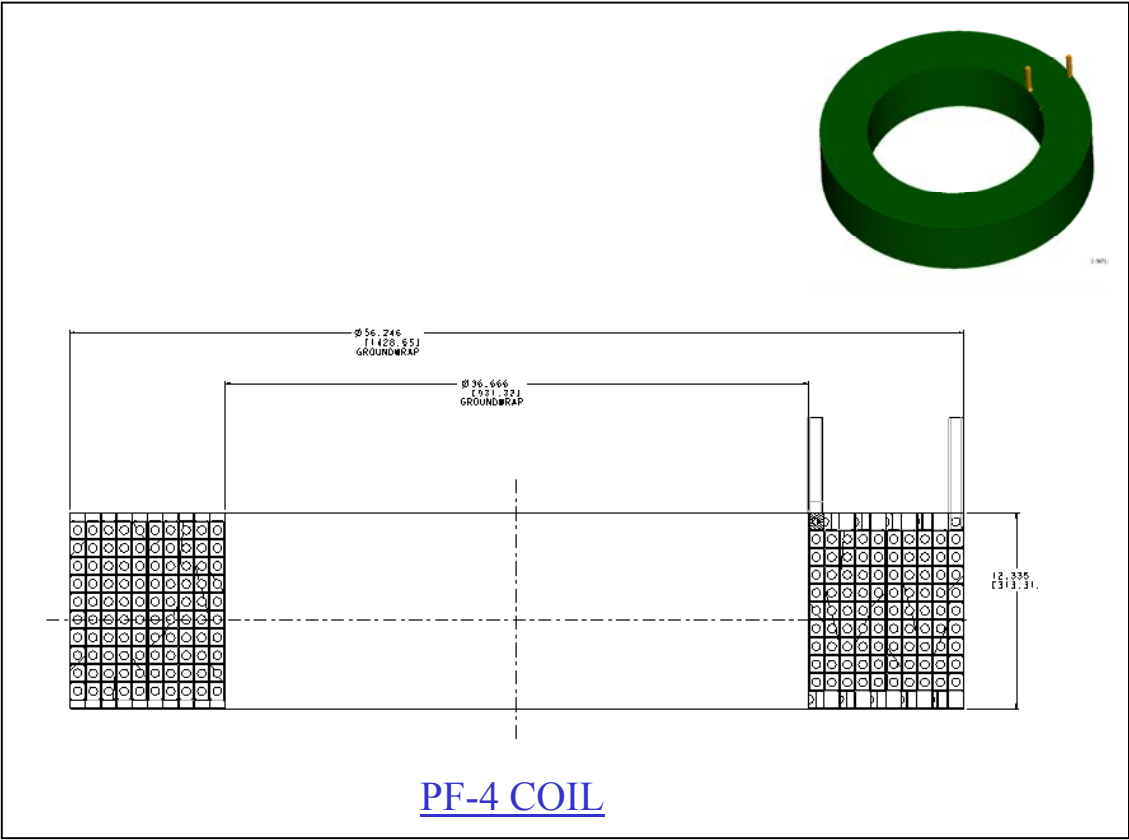
8.0 DELIVERABLES

The Subcontractor is responsible for delivering to PPPL the following:

- a. All documentation listed in section 6.0.
- b. Completed coil assemblies which have successfully passed all acceptance tests and criteria.
- c. Balance of materials supplied by PPPL or which were procured by Subcontractor solely for this contract.
- d. Fixtures or tooling fabricated solely for the fabrication of these coils.

Appendix I. Preliminary Coil Drawings





PF-3 Coil
Details

