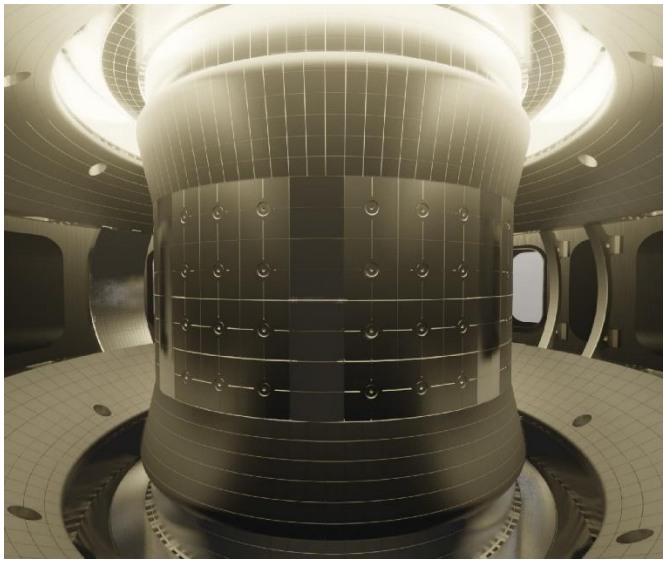
Fabrication procedure PFC - CU_v1_4.docx

This document represents a working version therefore some chapter numbers may be not correctly linked or finished



IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

MINISTRY OF EDUCATION, YOUTH AND SPORTS

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Table of content

1 Introduction

Disclaimer: The purpose of this section is to give a general overview and show a context of the tendered system – the Poloidal Field coils. The detailed description for manufacturing, defining the subject of the tender, is in chapter 5 and in the attached technical drawings (Annex ?).

There are several types of coils on the COMPASS-U tokamak with different function and geometry: Toroidal Field coils (TF) creating the toroidal magnetic field, Poloidal Field coils (PF) and Central Solenoid (CS) coils creating the poloidal magnetic field and Correction coils distributed on the inner side of the tokamak vacuum vessel for control of the toroidal symmetry of the magnetic field. The scope of this particular contract is the set of PF coils.

There will be 10 poloidal field coils in total (five pairs). The five upper coils are named PF1aU, PF1bU, PF2U, PF3U and PF4U, detailed parameters are shown in Table 3-1, their counterparts are lower coils PF1aL, PF1bL, PF2L, PF3L and PF4L. Upper and lower coils form pairs, but are not exactly symmetrical, e.g. they differ in current feeders' and coolant feeders' placement. The winding pattern of the coils is optimized for error magnetic fields in the vacuum vessel and will be provided in drawings for each coil. Coils shall be wound from a hollow conductor to allow flow of cooling medium - gaseous helium. Each PF coil will have to accommodate multiple separate cooling circuits. Coolant inlet will be made of copper - stainless steel electrical break with Swagelok VCR connection. PF coils current feeders are formed by parallel conductors.

Each coil will be made of several separate conductors forming the individual cooling circuits. The advantage of the concept is that the joint of cooling channels can be done outside of the poorly accessible area inside the TF coils. The electrical connection of the separate coil windings creating these cooling circuits must be ensured.

Requirements are delineated in the following paragraphs. Seller 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.

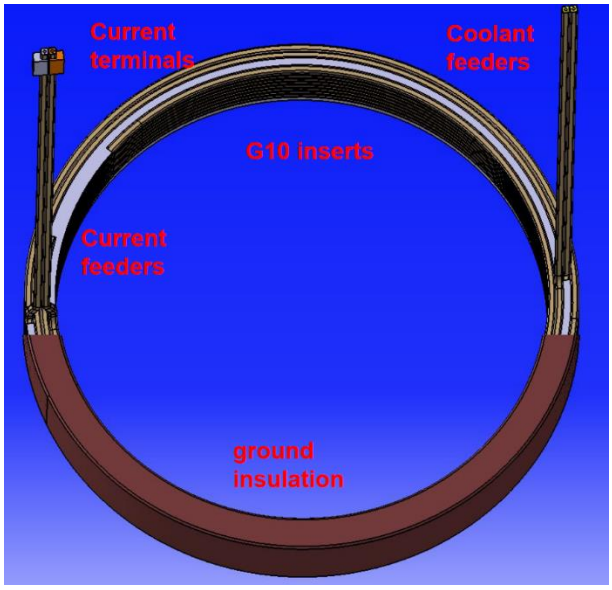


Figure 1.1 - Illustrative picture of one of the PF coils.

2 Terminology, dictionary and abbreviations

Buyer	the contracting entity – Institute of Plasma Physics of the Czech Academy of Sciences
Seller	the entity contracted to manufacture the PF coils, selected as a winner of the tender
ABD	As-built Documentation (final documentation of real manufactured equipment)
AD	Accompanying Documentation (operational and maintenance documentation)
COMPASS-U	COMPASS-U: Tokamak for cutting-edge fusion research
CS	Central Solenoid
PF	Poloidal Field
TF	Toroidal Field
GF	glass fibre
LN temperature	liquid nitrogen temperature (T = 77 K)
MIT	Manufacturing, Inspection and Test plan
FAT	Factory Acceptance Tests
SAT	Site Acceptance Tests
MIC	Manufacturing Interim Check – tests performed during the manufacturing process
VCR	VCR fitting type from Swagelok
PF1xx-PF4x	abbreviation denoting all coils (PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L), except the prototype coil
Basic Configuration	the set of deliverables which will be ordered together within the contract
shall	means “must” or “mandatory”
PSS	Power Supply System
SFPS	Shaping Field Power Supply

VS	Vertical Stability
EFPS	Equilibrium Field Power Supply
FA	Fast Amplifiers
FF	Fast Feedback
IPP	Institute of Plasma Physics (of the Czech Academy of Sciences) Equivalent to “the Buyer” or “the Buyer’s site”.
Machine Protection	The system used to protect the tokamak against damage (e.g. the Machine Protection system can request to stop the currents supplied by the Power Supply System). The system is not part of the delivery, it belongs and it is operated by the Buyer
Personnel Interlock	The system used to protect people entering the experimental area (e.g. tokamak hall). The system is not part of the delivery, it belongs and it is operated by the Buyer.

3 “Poloidal Field Coils for COMPASS Upgrade tokamak”: Extent of delivery

The “Poloidal field coils for COMPASS-U tokamak” (“contract” in this document) includes manufacture, development of tooling, purchase of materials, design of individual “non-critical” parts which are not prescribed by coil design, testing and transport to a place specified by Buyer.

For the purpose of the procurement procedure, the “Poloidal field coils for COMPASS-U tokamak” is divided into these parts:

1) Manufacture and testing of a prototype coil

   The purpose of this part is to test the implemented solution and Seller’s technical ability to manufacture the coils of the requested quality. If the prototype coil fails to meet the requested criteria, the Buyer reserves the right to cancel the contract. PF1aU coil is chosen as the prototype coil – it will be made as an extra coil aside the set of 10 PF coils described in point 2) below. Based on the experience with manufacture and subsequent tests, minor modifications of the specifications to improve the coils design and manufacturability are possible, see section 7.3.

2) Manufacture of coils

   Winding, insulation and impregnation of the set of 10 PF coils. The basic PF coils parameters are summarized in the Table 3-1 below.

Table 3-1 Basic PF coils parameters

	coil	conductor

Coil name	median radius [m]	cross-section (incl. insulation)		coil mass [kg]	approx. number of turns	height [mm]	width [mm]	Cooling hole diam. [mm]	corner radius [mm]	length of conductor [m]
		dR [m]	dZ [m]							
PF1aU, PF1aL	0.576	0.0785	0.15	197	33	15	15	7	1	119
PF1bU, PF1bL	0.662	0.0785	0.15	227	33	15	15	7	1	137
PF2U, PF2L	0.749	0.075	0.15	257	33	15	15	7	1	155
PF3U, PF3L	1.06	0.120	0.10	387	37	15	15	7	1	233
PF4U, PF4L	1.42	0.121	0.195	889	38	20	17	9	1	360

*Note: Dimensions in Table 3-1 are provided for information only. Refer to the drawings for precise and complete dimensions, including tolerances.

3) Coil accessories
   a) Coil current and coolant feeder holders
   b) Rigs/jigs for coil manipulation and transport

4) Testing and delivery
   a) Material acceptance tests (confirming required material properties)
   b) Size and shape inspection
   c) Electrical testing (ground insulation, resistance, inductance)
   d) Cooling channels - leak testing and throughput
   e) Paschen tests
   f) Delivery of manufactured PF coils to a place specified by the Buyer (in the Czech Republic)

5) Technical drawings, manufacturing protocols, certificates (see section 3.2)

3.1 Physical deliverables

The list of the physical deliverables is in Table 3-2, including expected delivery dates.

Table 3-2 - List of physical deliverables.

Item	**Count**	**Delivery date**	**Specification**

			reference
Insulation mock-up and test samples	1		
Prototype coil PF1aU	1		
Coil PF1aL	1		
Coil PF1aU	1		
Coil PF1bL	1		
Coil PF1bU	1		
Coil PF2L	1		
Coil PF2U	1		
Coil PF3L	1		
Coil PF3U	1		
Coil PF4L	1		
Coil PF4U	1		
Stainless steel holders for the coils connections			
Material samples			
Rigs/jigs for coils manipulation and transport			
Other tooling for manipulation			
Packing material			

Please note the coils are supposed to be delivered in order, the lower ones first (PF1aL, PF1bL and PF2L → PF3L → PF4L), the upper later (PF4U → PF3U → PF1aU, PF1bU and PF2U), to fit the sequence of the tokamak assembly. The details of the storing and transportation are in chapters 7.1 and 7.2. The cost of storage up to the date indicated by the schedule of delivery in the Table 3-2 is expected to be included in the coils price. The costs of potential additional storage shall be priced in the bid separately, per coil and month.

3.2 Document deliverables

All documents shall be provided in digital (PDF files, 3D models in STEP or Catia files) format. Documents are listed in Table 3-3.

Table 3-3 - List of document deliverables.

Deliverable item	When required	Specification reference
QA Plan	Prior to any manufacturing, inspection, or test activities specific to the scope of supply of this specification, including its further revisions.	8.1
Manufacturing and tooling drawings	Prior to use.	
List of Seller-supplied materials	Prior to procurement of materials and whenever their list is revised.	5.9
Certified Material Test Reports for conductor		6.1
Design of VPI mold and sealing features	Prior to use.	5.9.16
Manufacturing/Inspection/Test (MIT) plan, template	After receipt of order, for IPP approval prior to the start of manufacture.	7.4
Procedures identified in the MIT	Prior to any manufacturing, inspection, or test activities specific to the scope of supply of this specification	7.4
Protective measures in clean area during operation that could produce chips and filings	Prior to work.	5.8.1
Non-conformance reports	Immediately following detection.	7.3
Non-conformance on dimensions	Immediately following detection.	7.3
Procedure for repair of damaged insulation	Prior to use.	6.5.1
Impedance test procedure	Prior to use.	6.5.1
Resistance test procedure	Prior to use.	6.5.1
Pre-VPI electrical test results	Immediately following testing.	5.8.6, 6.5.1
Connection procedures	Prior to use.	5.8.9
Connection procedures qualification – examination of samples report	Prior to connection operations	5.8.9
Connection procedures operators' qualification report	Prior to operations.	5.8.9.3
Dimensional Inspection of completed coil	Prior to submittal of IPP Shipping Release Form.	6.5.2
Photographs of packed and crated items	Prior to submittal of IPP Shipping Release Form	7.2

4 Specification for the Seller's Bid

The Seller's bid shall provide pricing of the items as listed in the Table 4-1. Please note this table is not exactly same as Table 3-2 (Physical deliverables). The Contract will cover items 1-11 as a Basic

Configuration, which will be ordered together. The price of documentation (e.g. MIT plan, test reports, …), prototypes, tooling and manipulation accessories, etc. is expected to be included and distributed over the items 1-11. The items 12 and 13 …

Table 4-1 - List of items for pricing in the bid.

	Item nr.	Item description	Notes
Basic configuration	1	Prototype coil PF1aU	
	2	Coil PF1aL	
	3	Coil PF1aU	
	4	Coil PF1bL	
	5	Coil PF1bU	
	6	Coil PF2L	
	7	Coil PF2U	
	8	Coil PF3L	
	9	Coil PF3U	
	10	Coil PF4L	
	11	Coil PF4U	
optional	12	Paschen test – one of coils PF1-PF3	
optional	13	Paschen test – one of coils PF4	

5 Technical specifications and requirements

5.1 Coil mock-up and insulation sample

5.1.1 Insulation sample

Two copper plates are wrapped by two layers of half overlapped glass fiber (GF) tape interleaved with Kapton , then one layer of half overlapped GF tape and then VPI is used to join them together with resin

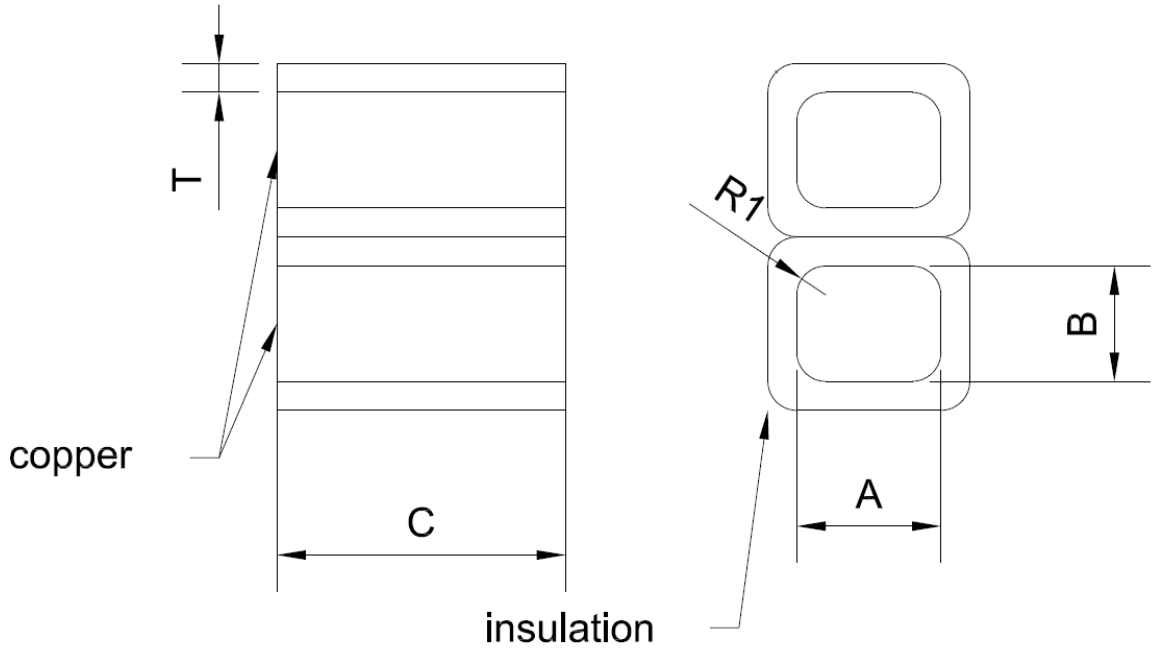
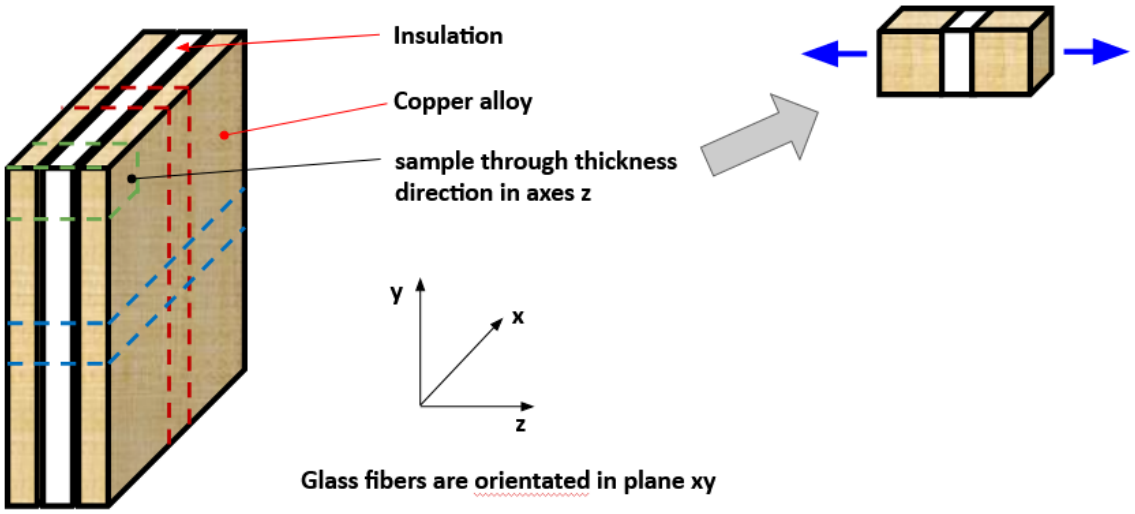


Fig. 1 Sample 1 (copper plates wrapped by fiberglass tape with Kapton).



3 samples for through thickness direction for tensile testing at 300 K by EN ISO 6892-1

3 samples for through thickness for tensile testing at 77 K by EN ISO 6892-3

Values give by COMTES

Shear – compression tests

Specification according COMTES data

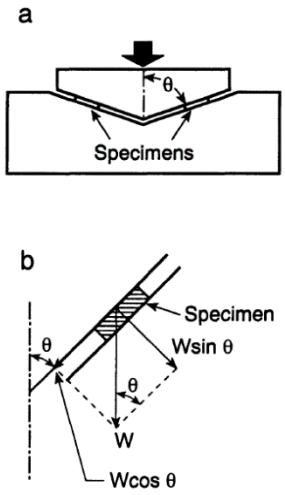


Figure 1. Schematic of test fixture used to simultaneously load, in parallel, 5 × 5 × 1.1 mm test specimens in shear and compression.[1,2]

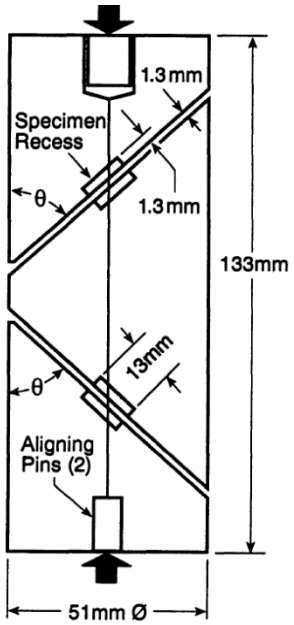


Figure 2. Schematic of test fixture used to simultaneously load, in series, 13 × 13 × 8.1 mm test specimens in shear and compression.[5,6]

example

5.1.2 Coil mock-up

The mock-up shall demonstrate the technology of insulation of the coils. Coil mock-up shall simulate part of the PF1a coil. Specification:

- Minimal assembly of 3x3 hollow conductors (same conductor like in 5.9.1).
- Minimal length of mock-up 250 mm.
- Coated with primer (see chapters 5.8.2.3, 5.8.4, 5.9.4).
- Wrapped with turn, inter-layer and ground insulation, mimicking the insulation layers as described in 5.9.5.
- Impregnated as described in chapters 5.8.7 and 5.8.8.
- The turn insulation layer is extended min. by 10 mm beyond the conductor ends to prevent tracking discharge at the free ends during the turn-to-turn HV test.

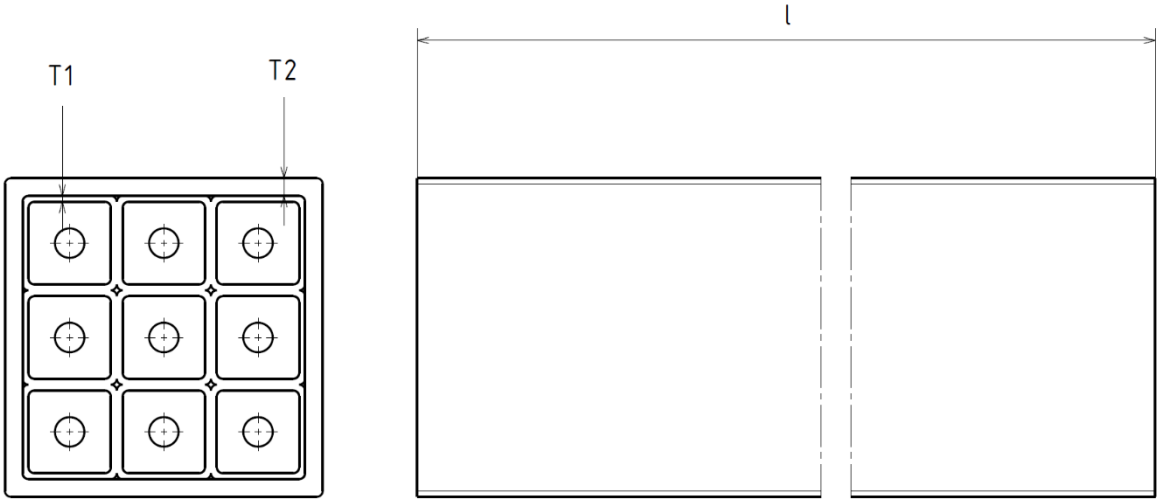


fig. 1 Mockup sample

Tests demonstrated on the sample in this order:

Sequence	activity
1	Visual inspection and photographs with ×50 augmentations
2	Insulation resistance test (IR) measured as is describe in 5.2.1 to check turn to turn (T-T) insulation and ground insulation (GI)
3	DC Hipotest (T-T, GI) according to chapter
4	5 thermal cycles between 300 and 77 K (liquid nitrogen temperature)
5	Insulation resistance test (IR) measured as is describe in 6.3.3 to check turn to turn insulation and ground insulation
6	DC Hipotest (T-T, GI) according to chapter
7	
8	Visual inspection and photographs with ×50 augmentations
9	DC breakdown (T-T) at room temperature
10	*Cross sections examination*. Minimally 3 slices with thickness of 50mm were cut from the long mock-up to check the cross sections optically. Polishing is used to prepare the slices before photographing;

5.2 Prototype coil

The prototype coil will be manufactured to demonstrate feasibility of the design. The prototype coil will be the same as PF1aU. The coil will be tested in order to find any design flaws, including “destructive” tests for inspection of the conductor and insulation cross-section. The samples will be provided to the Buyer, as described in the chapter 6.

5.3 Poloidal field coils

The poloidal field coils PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4L and PF4U are defined by the drawings. Here we describe only details which are not self-explanatory from the drawings.

5.4 Electrical breaks

The electrical breaks insulate the coil conductor from the cooling circuit piping, to avoid electrical current penetrating the cooling system. The inlet part of the electrical break is made of copper, outlet is made from stainless steel and these parts are insulated from each other by a ceramic material. These breaks are connected with VRC fittings (Figure) and will be supplied by IPP, in sizes corresponding to the cooling channel dimensions. Breaks will be welded by orbital welding machine to all cooling channels terminals (as is shown in drawings). These breaks should be insulated with same FG and Kapton tapes layer pattern (fig. xx) as PF coils till VCR fitting and VPI-ed with resin. The endings of VCR fitting have to be protected against intrusion of resin and clogging of cooling channel.

The electrical breaks will be provided by the Buyer.

Figure 5.1 - Electrical break with VCR fitting.

5.5 Soldered joint of hollow conductor

At dedicated places are soldered joints which shorten current path of feeders which transferred the coolant medium out/into the coil. These places are soldered together for electrical contact to ensure the current can continue through the coil turns, while the other end of hollow conductors are routed out from the toroidal fields (TF) coil. Outside the TF coils area the hollow conductor is connected to the electrical breaks. Solder joints are specified by drawings and in chapters 5.9.12 and 5.10.3.

5.6 Feeder support constructions

The points where the hollow conductors are of soldered together, the supporting structures are used.

Manufacture of these parts is a responsibility of the Seller and will be supplied with coils. All these parts have to be made from diamagnetic material as is indicated in drawings.

5.7 Coil accessories

The rigs/jigs for the coil manipulation and transportation shall allow safe operations. It shall allow to turn the coils upside down (transport, inspection, storage and installation). It is proposed to design universal rigs for the manipulation, e.g. one piece for the smaller coils (PF1xx, PF2x, PF3x) and one piece for the bigger coils (PF4x).

5.8 Fabrication

5.8.1 Cleanliness/housekeeping

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

5.8.1.1 Clean environment

The final preparation of all insulating materials, the final preparation of the mold, the application of insulation, and the winding of the coil must be performed in a clean, humidity controlled environment that eliminates the risk of debris and dust particles such as metal chips, dirt, etc., from contaminating the coil insulation prior to VPI. 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 5.8.1.3), and shall employ a positive pressure fan with a HEPA filter.

5.8.1.2 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.

5.8.1.3 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-10 fillers or other components used in the construction of the PF coils. 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.

5.8.1.4 Markers and Pencils

The use of electrically conductive pencils is prohibited in the fabrication stations due to electrical tracking concerns. Markers used on the conductor may affect adhesion of the insulation – compatible type of markers has to be discussed with the primer/epoxy manufacturer. Used brand and type of markers have to be approved by the Buyer.

5.8.1.5 Chips and filings

Filing, grinding, or any other operation that generates any kind of electrically conductive chips shall not be allowed in the clean area (section 5.8.1.1). 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. If such an operation is not planned but is needed (e.g. removal of burrs on conductor) the protective measures to prevent contamination of insulation shall be reviewed and approved by the Buyer in advance of the work.

5.8.1.6 Material Protection

Material controls shall be addressed in the QA Plan (section 8.1) or MIT Plan (section 7.4). 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 from skin oil, etc. (see section 5.8.1.3). The winding line shall be covered during off-shifts.

5.8.2 Copper receipt, inspection and handling

5.8.2.1 Identification

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

5.8.2.2 Receipt inspection

Upon arrival of each shipment of conductors, Seller 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 Buyer-approved NCR disposition. Repairs should be photographed. This receipt inspection step shall be delineated on the MIT plan.

5.8.2.3 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 unwinding and rewinding. When the conductor is transferred and when it is fed into the winding line it shall be inspected and any surface defects shall be repaired. Immediately prior to application of the turn insulation, the conductor shall be grit blasted and then 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. Then the primer shall be applied. After the primer dries properly, the glass fibre tape with Kapton (where specified) shall be wound on the conductor.

During winding of primed conductors, the method used to maintain conductor tension cannot use a friction method that would damage the primer coating.

5.8.3 Conductor bending

kvalifikacni vzorky ohybu s malym polomerem (bez izolace), na tech udelat testy s RTG i vybrusem.

For conductor from PF1a and PF4 coil are made three bends with smallest radius according to drawings

5.8.4 Key winding steps

Key steps of the winding sequence are described in this section. The Seller shall include all winding steps in the MIT and sub-tier procedures referenced by the MIT.

5.8.4.1 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 spacers in place must also be taken to ensure the spacers do not shift during winding. Planning and measurement is 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.

5.8.4.2 Turn insulation

The turn insulation shall be applied to the conductor using an automated taping machine so that precise control of dimensions is achieved. If the Seller identifies critical locations, where automated taping is not possible, it must be agreed with the Buyer to use manual taping (with written approval). 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 5.9.5 for turn insulation details.

5.8.4.3 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. 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 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 the Buyer before continuing with the winding process.

5.8.4.4 Start and finish leads

The insulation shall be tailored to ensure that the number of overlapping layers of glass and Kapton on the turns is retained on the leads.

5.8.5 Handling of coil prior to VPI

Care shall be taken to avoid damage to the insulation in subsequent handling. 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 by the Buyer before use.

5.8.6 Pre-VPI electrical tests

For details see chapter 6.

5.8.7 VPI preparations

5.8.7.1 Mold cleaning

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

5.8.7.2 Mold leak test

Before VPI the mold has to be leak tested – see details in 6.4.

5.8.8 VPI and curing

The VPI and curing process shall include the following steps. Parameters to be measured and recorded, along with acceptance criteria, shall be delineated in the MIT.

- Leak check and/or rate of pressure rise test
- Resin fill volume measurement (recommend expanding a pressurized volume of nitrogen into the evacuated VPI mold and performing delta pV calculation).
- Bakeout/de-gassing of the coil and resin delivery system.

- Weighing, mixing and degassing of the resin (to be de-gassed to a pressure less than the vacuum pressure during VPI)
- Filling process including fill rates at each inlet and soak times
- Milking process (reverse flow under positive pressure) after fill is complete.
- Determination of the quantity of resin that was used to impregnate the coil and comparison with expected fill volume based on fill volume measurement.
- Oven temperature ramp rates and hold times with each step annotated on the chart and MIT (beginning ramp up, end ramp up, etc.)

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.

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).

5.8.9 Metal connection qualification program

Seller shall qualify the metal connection procedure (Braze, solder, Ultrasonic welding, etc.), equipment and operators prior to use. Metal connection qualification requirements are as follows.

This section is applicable to:

- brazing of current terminals
- soldering of coolant feeder
- welding of electrical break on the coolant inlet

5.8.9.1 Procedure

The selected coil manufacturer shall develop a metal connection procedure for performing the lead terminals. Procedure shall be reviewed and approved by the Buyer.

5.8.9.2 Qualification of Procedure/Process

A minimum of three (3) successful metal connection samples shall be made to qualify the metal connection process and settings.

This qualification includes thermal cycling and tests leak tightness. Thermal cycling shall consist of at least 3 cycles between LN2 and room temperature (with controlled ramp-down/ramp-up ?°C/min). The leak tightness test shall be performed before and after thermal cycling on all 3 test samples.

5.8.9.3 Qualification of metal connection Operator

A minimum of three (3) successful metal connection samples shall be made by each metal connection operator to qualify his/her ability to perform successful metal connection (these may be the same samples used for procedure qualification).

5.8.9.4 Qualification Requirements

A visual inspection of the finished joint (on the connection qualification samples) shall be made to confirm complete flow of material into the joint area. The joint shall be free from all cracks under 10x magnification. Qualification shall be documented along with the samples provided to the Buyer for their examination and concurrence before production of metal connection begins.

5.9 Materials

All supplied materials shall be inspected upon receipt and any discrepancies, deviations, or other defects shall be noted and communicated to the Buyer and supplier as soon as possible. The excess materials are property of the Seller, the Buyer requires only samples from each production/delivery batch (as described in 6.1).

5.9.1 Conductor

The conductor material will be C10700 oxygen-free silver bearing copper. Nominal dimensions and characteristics (at room temperature) are given in Table 5-1.

Table 5-1 - Conductor properties.

Chemical composition and corresponding standards:					
	Composition* Ag content [%]		EN – CEN/TS 13388:2008	ASTM / USA	
HK015	0.085 – 0.12		CuAg0.10 (OF) / CW019A	CDA C107 OFS	
	** Other elements max %: Bi 0.0005, others total 0.0065*				
Physical properties					
Density [kg/dm^3]	Coef. of linear expansion [1/K]		Specific heat [J·kg^{-1}·K^{-1}]	Melting temperature [°C]	
8.94	0.0000177		385	1083	
Electrical and thermal properties – typical values:					
Electrical conductivity			Electrical resistivity		Thermal conductivity (20°C)
vol [% IACS] **	mass [% IACS]	MS/m	vol [Ω·mm^2/m]	mass [Ω·g/m^2]	[W·K^{-1}·m^{-1}]
min 99.5	min 98.9	min 57.7	max 0.0173	max 0.1549	388
*** % IACS = International Annealed Copper Standard. The % IACS values are calculated as percentage of the standard value for annealed high conductivity copper as laid down by the International Electrotechnical Commission.*					

Use of grit blasting, wiping with alcohol and priming (see section 5.8.2.3) of the conductor is necessary to ensure good adhesion of the resin to the conductor.

Table 5-2 - Minimal yield strength of the conductor in the completed coils.

Coil	yield strength [MPa] (0.2% elongation) at room temperature (293 K)
PF1aU, PF1aL	> 260
PF1bU, PF1bL	> 200
PF2U, PF2L	> 175
PF3U, PF3L	> 220
PF4U, PF4L	> 90

5.9.2 Cooling pipes

The cooling pipes shall be manufactured from the hollow conductor with same specification as the coil's conductor (section 5.9.1), e. g. from square/rectangular cross-section shape, machined to the circular cross-section, according to the drawings.

5.9.3 Mandrel

Seller is responsible for developing removable winding mandrel for production of "bare" coils.

5.9.4 Primer

The primer improves adhesion between the conductor and epoxy resin of the insulation. The thickness of the primer coating shall be maintained within the range specified by the manufacturer. The application procedure is prescribed by manufacturer and shall be followed.

Prescribed primer:

Product name: CTD-450

Manufacturer: Composite Technology Development Inc. 1505 Coal Creek Drive Lafayette, Colorado 80026, (303) 664-0394

5.9.5 Insulation layout

This section describes insulation system proposed by the Buyer. If an alternative solution is proposed, the Seller must demonstrate the properties (namely …, …) are equivalent or superior to the proposed solution.

Table 5-3 Working voltage and frequency of power supplies for PF coils.

coils	voltage [kV]	frequency [kHz]
All PF	1	0.5 - 2

conductor insulation

2 layers of e-glass tape interleaved with Kapton tape with 50 % overlap. Kapton tape width will be at 80% of glass fiber tape. Width of GF tape is suggested by seller, depends on size of the conductor.

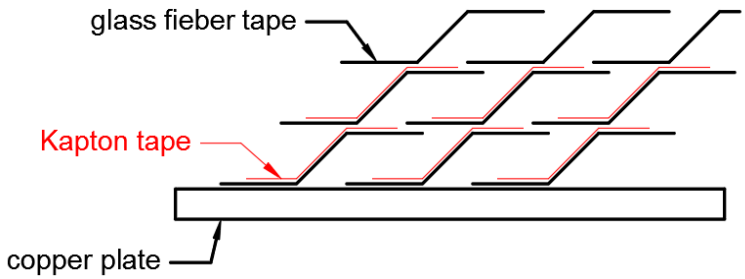


Figure 5.2 Conductor insulation – sketch of glass fiber and Kapton tape layup.

Note: The tolerance for a half-lapped layer is defined as the half of width of the used tape, so that there is a minimum of a half-lap layer with the possibility of exceeding the overlap with the second half. Around the bends, this tolerance applies to the outer diameter where the inner diameter is allowed to exceed the additional 0.3 mm 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.

ground insulation

10 layers with 50 % overlap of e-glass tape, Width of GF tape is suggested by seller, depends on size of the winding pack/coil dimensions.

Electrical conductive layer

Part of the ground insulation will be one layer of conductive mash

5.9.6 Resin

The application procedure is prescribed by manufacturer and shall be followed.

Product name: CTD-101K

Manufacturer: Composite Technology Development Inc. 1505 Coal Creek Drive Lafayette, Colorado 80026, (303) 664-0394Primer coating for VPI

5.9.7 Polyimide tape

Product name: DuPont™ Kapton® FPC, thickness 0.025 mm

Manufacturer: DuPont

5.9.8 Glass fibre

All glass tape must be E-glass woven from yarns made of continuous filaments with no more than 1% alkali-E glass. The filaments shall be amino-silane treated before weaving to improve wetting during resin infusion. The glass tapes shall be 8H satin weave tape, weight 300g/m2 ±2%.

The glass content of the insulation shall be 55% ± 5% volume in order to match the coefficient of expansion of copper to that of the insulation.

Resin-rich areas are not permitted. Particular care shall be taken to ensure that the glass content specified above is obtained in and around the end turns and formation of the tails.

5.9.9 Shims and Spacers

The Seller will manufacture G-10 winding shims and spacers as indicated on the Buyer's drawings. Lead blocks and fillers are to be inspected prior to assembly for burrs or sharp edges and de-burred if necessary. The parts shall be cleaned with an appropriate solvent prior to use.

5.9.10 Tooling

All tooling (including the VPI mold) shall be supplied by Seller. The design of tooling used for fabricating the deliverable items of the contract shall be reviewed and approved by the Buyer prior to use.

5.9.11 Coil terminal blocks

Machined blocks for coil terminals shall be fabricated from a copper bar or plate per the Buyer supplied drawings. Certified Material Test Reports (section 8.15.1) shall be provided for the materials used.

5.9.12 Braze and solder materials

Suitable braze material will be supplied by Seller. Brazing will be done at room temperatures but brazing material has to be suitable for cryogenic temperatures (up to LN temperature).

Recommended are these materials but seller can suggest alternatives with same or better properties
for soldering: $Pb_{93.5}Sn_5Ag_{1.5}$
for brazing: $Ag_{72}Cu_{28}$ or $Ag_{60}Cu_{30}Sn_{10}$

5.9.13 Coil lead and transition fillers

Any required fillers not supplied by the Buyer shall be supplied by Seller. The insulating lead blocks and coil fillers shall be constructed from G-10. Material Certifications (section ?) are required. All machining of G-10 must be done in the way to comply with its use in a high vacuum environment. The fillers and lead blocks shall be free of burrs and sharp edges. All G-10 surfaces unless machined shall be sanded to remove any high gloss surface, to promote bonding of the epoxy to the lead blocks. The parts shall be cleaned with an appropriate solvent prior to use.

5.9.14 Void materials

All regions within the winding volume not occupied by conductor or ground insulation shall be filled with certified (section ?) E glass or G-10 fillers to minimize resin rich areas. When using E glass to fill voids, the glass shall be densely applied to avoid resin rich areas. Void areas (filled with resin) where there is no glass or G-10 filler shall not exceed 0.8 mm. The edges of G-10 shall be radiused (0.5 mm to 1.0 mm) to prevent damage to adjacent insulation. The G-10 fillers shall not be in direct contact with other G-10 components without intermediate layer of GF tape insulation.

5.9.15 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 Seller shall be approved by the Buyer prior to use. Recommend solvents are acetone and alcohol, however only alcohol is permitted for use on the primed copper.

5.9.16 VPI Mold

Seller shall supply the VPI mold. The design of the mold and sealing shall be submitted to the Buyer for review and approval (refer to section ?).

5.9.17 Mold release

Seller shall propose a mold release agent for use on the surfaces of mold parts that are to be removed after VPI. Mold release material shall be proposed by Seller and approved, in writing, by the Buyer prior to use.

5.9.18 Holders for current terminals

Material can be stainless steel 316 LN or stainless steel 316 L but with these bulk permeability:

stainless steel 316 LN bulk permeability $\mu < 1.05$

stainless steel 316 L bulk permeability $\mu < 1.4$

5.9.19 Other materials

All other materials not listed in section 5.9 or above required to fabricate, test, and ship the deliverable items shall be supplied by Seller. Additional insulating materials provided by Seller shall be reviewed by the Buyer prior to purchase to verify compliance with this specification. All materials that become part of the coil must be certified (see section 8.15.1).

5.9.20 Material provided by Buyer

Electrical breaks

5.10 Operational environment – vacuum compatibility

The coils will be placed in cryostat, where the thermal losses are minimised by the vacuum environment. It means the coils must be High vacuum compatible $p < 10^{-5}$ Pa.

5.10.1 Dead spaces

Hidden voids, where gas can stay trapped, must be avoided. The surfaces of the materials shall not be porous. The surfaces shall be free of substances degrading vacuum, e.g. residues of lubricants from machining, solvents from cleaning, etc. The cooling channels shall be leak tested (see chapter ?).

Parts that are part of the vacuum system (i.e. parts which serve as a barrier from the atmosphere or operating fluids) have to be manufactured as **leak free**. This property must be verified by a leak test according to the norm **EN 1779** - "Leak detection method classification" and **ISO 20485:2017** - **"**Non-destructive testing — Leak testing — Tracer gas method". Target value of the leak test is 1e-10 Pa m3/s .

All components must be designed and manufactured in such a way as to prevent the formation of trapped volumes causing **virtual leaks** (i.e. a trapped volume is an empty space connected to vacuum through a very small hole, having a low vacuum conductance).

5.10.2 Welded joints

All welds seams on vacuum components must be free of pores and cracks (this may cause leakage or acts as outgassing source).

Welds shall be done preferably on the vacuum side of the components. If it is not possible, full penetration welds have to be done.

Welding under inert gas or vacuum is preferred to avoid introducing of foreign material into the weld and consequently production of cavities and cracks.
For welded joints, the parts have to be cleaned properly prior to welding to avoid accumulation of contaminants and consequent hot cracks.

All the welds must be pickled and passivated, either by using a chemical agent (pickling gel/solution) or by using an electrochemical pickling machine. Any pickling solution used must be afterwards neutralized and thoroughly cleaned.

If the selected welding procedure uses flux (shielded metal arc welding, flux cored arc welding, etc), all the flux residues must be completely removed.

Grinding down and polishing the welds is not required.

5.10.3 Soldered and brazed joints

All soldered and brazed joints have to be designed in such a way that it will avoid arising of closed volumes which can lead to creating virtual leaks.

All used solders and brazing alloy should be preferably vacuum compatible. Standard solders/brazing alloys can be used depending on the level of an achieved vacuum level and only after approval of buyer.

If flux is necessary to use during soldering or brazing, all the residues have to be completely removed.

Usage of water-soluble flux is preferred.

5.10.4 Surface finish

All the surfaces must be either machined, ground, glass-bead blasted, shot peened or polished - without surface oxides. Recommended surface roughness is R_a 25 or better, however the target is to minimize real surface area, not necessarily to improve roughness.

5.10.5 Suggested cleaning procedure for epoxy resin composites:

All conductors, insulations, 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.

Recommended solvents are acetone and alcohol, however only alcohol is permitted for use on the primed copper.

Cleaning procedure and solvent selected must be approved by IPP prior to use.

5.11 Dimension and tolerances

The tolerances of dimensions in the drawings provided by the Buyer are defined by Table 5-4, if not explicitly stated otherwise in the drawing. All values are valid for room temperature.

Table 5-4 - Tolerances for diameters (circularity)

diameter [mm]	from 400 to 1000	from 1000 to 2000	from 2000 to 4000
tolerance [mm]	±1	±1.5	±2

The tolerances of overall dimensions of the coils after manufacture are listed in Table 5-5.

Table 5-5 - Coil dimension tolerances

accuracy [mm]	PF1a; PF1b	PF2	PF3	PF4
total width	-0 mm +1 mm	-0 mm +1 mm	-0 mm +1 mm	-0 mm +2 mm
total height	-0 mm +1 mm	-0 mm +1 mm	-0 mm +1 mm	-0 mm +2 mm

PF1a, PF1b, PF2 shall have same height with tolerance

6 Testing specification

6.1 Material acceptance tests

All types of materials used for coils manufacture have to comply with the required specifications. Each production batch of the conductor has to be tested by the Seller (the tests can be outsourced at a certified laboratory) for the properties listed in Table 6-1. The stainless steel permeability shall be tested after delivery (Table 6-1). The other materials shall be accepted with “declaration of conformity” per every production batch, copies of all these accompanying documents shall be provided to the Buyer.

Samples of every production batch shall be kept and provided to the Buyer for later testing.

Table 6-1 – Material acceptance tests.

Material	Property	Expected value
Conductor	Mechanical strength	According chapter 5.9.1, Table 7.2
	Chemical composition	According chapter 5.9.1, Table 7.1
Stainless steel 316LN*	Magnetic permeability	μ< 1.05
Stainless steel 316L*	Magnetic permeability	μ< 1.4
Sample of insulation	Yield strength	According chapter 5.1.1, Table 7.1

In the case of Seller suggested solutions for insulation systems, these have to be tested to assure their compliance with the requirements made by Buyer.

6.2 Processed material tests

This chapter describes tests which shall be performed before manufacturing the actual coils, as a form of qualification of the manufacturing processes. The tests described here comprise of:

- insulation mechanical properties
- integrity of the bended conductor (see 6.5.3)
- integrity and leak tightness of the welded/brazed/soldered conductor and cooling inlets (see 5.8.9)

Table 6-2 - List of processed material tests.

Tested item	Test description	When required	
Insulation from the coil mock-up	yield strength	after mock-up is built	
	shear strength		
	GF in resin fill ratio		
Metal connection qualification sample	Leak tightness test before thermal cycling	before the first metal connection is performed on the prototype (or another	
	Leak tightness test after thermal cycling		

	Connection inspection ("X-ray")	coil)	
Prototype coil – most bended conductor parts (close to connection leads)	X-ray	after prototype is built	
	inspection in cut		
	copper hardness		
Prototype coil – conductor somewhere in the turns	yield strength	after prototype is built	
Prototype coil – cooling circuit	pressure and leak test	after prototype is built	
Prototype coil – metal connections	connection inspection	after prototype is built	
PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L coils – bended conductor	X-ray	FAT	
PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L coils – insulation sample	fill ratio?	FAT	
PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L coils – cooling circuits	pressure and leak test	FAT	
PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L coils – metal connections	connection inspection	FAT	

6.2.1 Integrity test of the bended conductor

The integrity of the conductor at the places with small diameter bends (indicated in drawing?) shall be checked. X-ray method is proposed for this task. To confirm X-ray inspection reliability, the prototype coil will be inspected with X-ray first and following mechanical cut on the selected bends will be inspected under microscope.

6.2.2 Metal connection integrity

The metal connections (welding/brazing/soldering) shall be inspected in 100% of their volume by a non-destructive inspection method. The Seller shall propose the inspection method in the MIT plan.

6.2.3 Leak inspection

These tests shall be performed on the metal connection samples (to check the connection is tight even

after thermal cycling) and also on the finished coils (all in the "Basic configuration", see Table 4-1).

The coil has to be air-flow tested to ensure that the cooling path is free from obstructions. Hydrostatic pressure test will be performed for 60 minutes (at 30 bar) to check that the coil is leak-free. No discernible loss of pressure or visible leaks are permitted.

The requirements for coils in the terms of pressure and leak rates are indicated in Table 6-3. Test pressures are 50% higher than the rated value, according to normal practice for pressure vessels.

The leak test can be performed using a standard leak detector or a residual gas analyzer. Required sensitivity and the correct function of the leak detector need to be verified in advance with a test leak.

Table 6-3 - Coils pressure and leak test parameters

circuit	nominal working pressure [Bar]	testing pressure [Bar]	max. leak rate [Pa.m^3/s]
PF	20	30	$<10^{-10}$

6.2.4 Push-out test

To be considered: Test mentioned in the paper *Huan et al., "Performance of the insulation mock-ups for the ITER PF6 coil", FusEngDes 2018*. Measure shear strength of the insulation/conductor interface by pushing the conductor out from the insulation; use the slice of the coil mock-up.

6.3 Electrical tests

Thermal cycle setup

Number of thermal cycles	3x
Temperature range	From Room temperature to LN2 Temperature
Temperature step	1K/min
environment	Atmospheric pressure air

Here is a general description of electrical tests, some are required during manufacture (pre-VPI), some for FAT, as is summarized in Table 6-4. Ambient temperature and humidity shall be recorded during the tests. Test results shall be reviewed and approved by the Buyer.

Table 6-4 - List of electrical tests

Tested item	Test type	Test parameters	When required	
Coil mock-up	IR test		immediately after manufacturing coil mock-up, part of this item's FAT; before	
	turn-to-turn	? 3kV		

	insulation test		and after thermal cycling	
	DC hipotest	7kV		
	DC breakdown			
Prototype coil	coil DC resistance			
	coil impedance and phase angle			
	IR test			
	VPI of the coil			
	IR test			
	thermal cycling of the coil (3x to LN2 temperature)			
	IR test		FAT	
	PD test		FAT	
	DC hipotest	7kV	FAT	
	Paschen?		FAT	
	coil DC resistance and impedance	for comparison with previous values		
PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L coils	coil DC resistance			
	coil impedance and phase angle			
	IR test			
	VPI of the coil			
	IR test			
	thermal cycling of the coil (3x to LN2 temperature)			

	IR test		FAT	
	PD test		FAT	
	DC hipotest	7kV	FAT	
	Paschen		on request – see ?	
	coil DC resistance and impedance	for comparison with previous values		

6.3.1 Coil DC resistance

DC resistance of the coil shall be measured at room temperature. Measured resistance shall match the nominal value (specified for each coil in Table 6-5) with tolerance of 5%. 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) and a nominal length of coil. Adjustment to the nominal resistance to correct for the as-built length of the wound coil is permissible.

Table 6-5 - Coils resistance and impedance (expected).

Coil	**Resistance [Ω]**	**Impedance [Ω]**
PF1aU, PF1aL	1.148E-02 ±5 %	
PF1bU, PF1bL	1.323E-02 ±5 %	
PF2U, PF2L	1.499E-02 ±5 %	
PF3U, PF3L	2.319E-02 ±5 %	
PF4U, PF4L	2.161E-02 ±5 %	

6.3.2 Impedance and phase angle measurement (Coil impedance test)

The test is non-destructive and can be used as the comparison test as the potential short-circuits are well seen.

AC impedance and phase angle shall be measured over the range 0.1 to 100 kHz. The values shall match values in Table 6-5. Impedance test device and test procedure shall be proposed by the Seller and approved by the Buyer.

6.3.3 Insulation resistance test (IR)

Test is commonly used and is also known as the Megger test. The advantages of the IR test is that it works with relatively low voltage ~ 1 kV and with low power devices. IR test provides the ability to detect main insulation failure.

Test have to be done according to **IEEE Std. 43-2000**.

The measured IR shall be >500 MΩ.

IR test should be carried before any other HV tests (test voltage > 1 kV). Fulfilling the acceptance criteria for IR test indicates good condition of insulation and correct setup.

The recommended voltage ramp is < 20 V/s because of the significant capacity of coil and feeders. Test starts at the moment when the voltage is equal to test voltage and the test time is minimally 1 minute but should be prolonged to take into account the capacitance of the tested object. The applied voltage, the measured current and insulation resistance shall be recorded every minute and plotted in a current vs. time graph. The table of the values and the graph shall be part of the test records.

Voltages: minimum is operational voltage, but significantly lower than for the hi-pot test. Defined in the norm.

The ground should be defined for the ground insulation testing, for example some conducting layer wrapped around the tested item.

6.3.4 Dissipation factor (Tan delta test)

Test has to be done according to **IEEE Std. 286-2000**.

Dissipation factor is equal to the tangent of dielectric loss angle. Tan delta test is complementary to Partial discharge test. Increase of dissipation factor is caused by the energy dissipated by the discharge in voids and cracks in insulation. The test should also detect delamination of the insulation.

Test measures the relative active and reactive components of current through the insulation under AC conditions, with the former due to the effective resistance of the insulation and the latter due to the effective capacitance.

Tan delta shall be measured at least at three (3) voltage steps: 0.2 U0, 0.6 U0 and U0. The tan delta difference between each step shall be part of the records.

The applied frequency of the AC voltage waveform shall be 0.1 Hz (Very Low Frequency Test) to facilitate the field testing. The frequency shall be clearly specified in the procedures and records. To avoid conditioning of the component, tan delta shall be measured again at 0.6 U0 after the highest voltage measurement.

6.3.5 Turt-to-turn insulation test

Power factor and tip-up test can be performed with the megger device.

Particular care must be taken during these tests to ensure that the partial discharge activity on unterminated coil leads do not result in substantial corona which could confuse the measurement. To reduce this effect, the leads can be enclosed, for example, in an SF6 environment. Protection measures must also be taken against arcing within the test circuit which, through transient voltages within the coil, can create local insulation failure and/or damage instrumentation and its wiring.

6.3.6 Partial discharge test (PD)

Test has to be done according to **IEC 60270**.

Scope of the test is to demonstrate the ability of insulation to withstand cyclic operation. During their lifetime, the tokamak coils will be energised 50 000 times (assumed amount of tokamak plasma discharges).

Partial discharge test is performed at the frequency of 50 Hz, so the 50 000 cycles correspond to ~17 minute testing time. For a successful test, it is necessary to measure more testing voltage cycles than the assumed number of tokamak plasma discharges. During the proof of principle test or development of the insulation, more than 1 hour long test is a useful tool.

Signal from the partial discharge test cannot be used directly. All measurements of the partial discharge in time are accumulated and synchronised in respect to the tested voltage. This PD "fingerprint" plot can be used also for a long term monitoring of insulation health.

Acceptance criterion is set to the absolute partial discharge level of <10 nC.

Signal levels have to be lower than criteria during all cycles.

Both turn-to-turn insulation or ground insulation test (insulation between two unconnected conductors or conductor and ground).

6.3.7 DC Hipotest

Test has to be done according to **IEEE Std. 95**.

The aim of the test is to prove that the system fits to the service against realistic overvoltage scenarios. For this reason the DC hipotest should be considered the final acceptance test of a commissionable part of the system.

The voltage shall be increased according to the ramp test method at a constant rate of 20 V/s. The application of a ramped voltage, instead of discrete voltage steps, linearize the absorption current component so that deviations in the leakage current are easily detected and allow the test operator to anticipate the end of the test in case of anomalies.The maximum test voltage shall be maintained for maximum 60 seconds.

IR test should be carried before DC Hi-pot test to check that the component is in good condition.

The test is successful and the component or system accepted if no evidence of distress and/or insulation failure is observed by the end of the total time of voltage application. Maximum tolerable leakage current could also be the acceptance criteria.

The applied voltage, the measured current shall be recorded in time and plotted in a current vs. time graph. The table of the values and the graph shall be part of the test records.

6.3.8 Paschen test

Specification of testing procedure:

- Tests shall be done at room temperature
- DC voltage shall be applied.
- The polarity should be such as to have the anode on the ground plane since the glow will appear in the anode environment.
- Pressure shall be swept from vacuum values to atmospheric ones. The testing voltage shall be maintained at each pressure decade for at least 1 minute
- Air is preferable.
- The final ground plane should be placed after the tests. The positive pole during the tests could be a metallic mesh placed around the coil that would allow the visualization of flashovers. A grounded vacuum vessel could also do the work with adequate precautions.
- The leakage current shall be continuously monitored (and never higher than the threshold given by the specified resistance of the insulation, which typically is 500 MOhm). Tests should be done twice, before and after the cooling down, and the leakage currents plots are compared.
- All problems detected with Paschen tests shall be repaired and the coils retested
- The ramp-up and ramp-down of the voltage to the nominal testing value should be done at a rate of 20 V/s.

Testing voltage: **3 kV**
Vacuum range: **10^{-2} – 10^{4} Pa**
Resistance of the insulation: **Riz ~ 500 MΩ**

6.4 Pre-VPI tests

Before completing the mold (refer to section 5.9.16) the dry coil shall be tested as indicated in the following sections. Ambient temperature and humidity shall be recorded. Test results shall be reviewed and approved by the Buyer before proceeding with VPI.

6.4.1 DC resistance and AC impedance

The DC resistance and AC impedance of the coil shall be measured and shall be in agreement with values specified in chapter 6.3.1.

6.4.2 Insulation quality test

Test procedure to measure insulation strength shall be proposed by Seller and approved by the Buyer.

6.4.3 Mold leak test

Prior to VPI, Seller shall demonstrate that the VPI mold is capable of achieving the base pressure, leak and out-gassing rates, as specified in the MIT, from room temperature up to the planned out-gassing temperature. …

6.5 Factory acceptance tests (FAT)

6.5.1 Electrical tests

The pre-VPI electrical tests described in section 6.4 shall be repeated, but in the insulation resistance test (section 6.3.1) the test voltage will be raised to 3 kV DC. Measured DC resistance values shall match the pre-VPI values. Measured AC impedance and insulation resistance values shall be consistent with the pre-VPI values, taking into consideration the differences arising from the presences of resin in the insulation. No electrical breakdown shall be observed. Ambient temperature and humidity shall be recorded. Test results shall be reviewed and approved by the Buyer as a prerequisite for shipment. Test procedures developed for section 6.4 shall address both the pre-VPI and final coil configurations,

accounting for the differences in test methods that may be required.

6.5.2 Dimensional Inspection

Dimensional inspection of the completed coil shall be performed. The dimensions shall be measured with a 3D metrology. An inspection report indicating all measured dimensions relative to their nominal shall be generated. Deviations beyond the tolerance shall be reported as a non-conformance.

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). 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 5 locations vertically along the inner and outer bore (80 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.

6.5.3 Integrity check

The integrity of the conductor at the places with small diameter bends (indicated in drawing?) shall be checked. X-ray method is proposed for this task. See chapter 6.2.1.

6.5.4 Leak inspection

The details of the leak test are in chapter 6.2.3.

6.5.5 Test & Inspection Matrix

The following table summarizes the tests, measurements and inspections to be performed on the coil. Additional testing and inspections that will be performed at the Buyer's site after the coil is delivered are listed as reference. Tests and measurements indicated in the "Acceptance Criteria" column, must meet the specified values in order for the coil to be considered acceptable to ship.

Table 6-6 Test & Inspection Matrix

Test	ref.	Pre VPI	Post VPI	Acceptance criteria	location	Notes
insulation test		yes	yes	no	Manufacturing site	
Impedance			yes	no	Manufacturing site	Compare pre and post VPI values

insulation test			yes	yes	Manufacturing site	Must pass acceptance criteria
Terminal DC Resistance		yes	yes	no	Manufacturing site	Compare pre and post VPI values
Dimensional Inspection			yes	yes	Manufacturing site and IPP	Conforms to drawing dimensions/tolerances
Visual evaluation sectioned coil			yes	no	IPP	Evaluate conductor spacing, VPI quality.
Hi-Pot of sectioned coil			yes	no	IPP	Determination of turn-to-turn voltage standoff

Table 6-7: List of FATs and SATs

No.	Name / description of the requirement	Valid for (which part of the steps/activities in the contract)	Required result
Dimensions tests			
1			
Electrical tests			
Leak tests			

6.6 Site acceptance tests (SAT)

Dimensions check, delivery integrity check

7 General assignment

7.1 Requirement on the temporary storage until delivery / installation in the Buyer premises

The temporary storage cost and delivery schedule are described in the Contract Conditions of this call. Here we describe only technical aspects of the storage.

The complete coils have to be stored in a dry place with temperatures in range … , not exposed to heat sources (sun or heating systems). The coils have to be wrapped to avoid dust accumulation and packed to avoid mechanical damage caused by the activities in the vicinity. Detailed requirements on packing are in the chapter about transport (7.2).

7.2 Transportation to the place of installation of the device

The formal requirements and schedule are described in the Contract Conditions of this call. Here are technical requirements:

- The coils shall be clearly labelled. The packing shall be labelled as well and shall contain clear instructions for manipulation.
- Before packing, the coils shall be clean; vacuum compatible and free from dust and debris.
- During the packing all requirements on the cleanness do apply (see chapter 5.8.1).
- All coils shall be carefully packed, to avoid contamination of the coils and their insulation during manipulation, storing and transport. Preferred material for wrapping is polyethylene. All materials shall contain minimum of volatile substances, which could potentially damage the insulation or conductor.
- The packing shall protect the coils from mechanical damage during all planned operations (lifting with crane, transport, etc.).
- The packing shall protect surface properties wherever functional essential (e.g. contact surfaces for electrical connection, surfaces for gluing the sliding pads, etc.)
- The openings of the cooling circuits shall be safely protected and sealed to avoid contamination of the channels.
- Adhesive tape, if used, shall not contaminate the surfaces of the coil.
- The coils shall be dry (incl. the cooling channels) at the moment of packing and the packing shall keep the coils dry.
- The amount of packing material shall be minimized, while the quality of packing shall not be compromised.
- The Buyer has a right to witness the packing procedure and thus shall be informed in time about planned operation (see section 8.9). After the packing completion, the package shall be sealed.

- All necessary rigs and jigs have to be supplied and are part of the contract. The rig for turning the coil from transportation position to the installation position shall be supplied (see 5.7).
- All necessary manipulation with the coil (incl. the rigs and jigs) shall be possible with a crane with 25 t lifting capacity (which is available at the place of installation).
- Delivery of the coils (PF1xx-P4x) is expected in three batches – the coils should fit onto three trucks. The timing of these deliveries will be subject of agreement, according to the actual situation.

7.3 Non-conformance and corrective actions

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

7.4 MIT plan

Seller shall submit a Manufacturing, Inspection and Test (MIT) plan for the Buyer 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 plan 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 Plan 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 Plan or a separate document, shall be used for data entry and operation sign-offs. Relevant data for inspections and tests include equipment ID and calibration status, acceptance values, actual values obtained, and pass/fail determination. The Buyer will designate selected steps as mandatory "witness" points. Seller shall notify the Buyer a minimum of five (5) working days in advance of these witness points (see 8.9). Revisions or changes to the approved MIT or traveler shall be reviewed and approved by the Buyer prior to use.

7.4.1 MIT plan evaluation and acceptance

The Buyer will evaluate the delivered MIT plan with following grading:

A) The MIT is complete and fulfils all requirements of the bid. Accepted without objections.

B) Minor flaws found in the delivered MIT plan, corrections and/or clarifications required. The Seller has 1 month for remedy. The re-submitted MIT plan is evaluated again in the same manner, but the deposit bound to this milestone (see **Error! Reference source not found.**) can be paid already.

C) Major flaws found, the MIT plan needs a revision. Seller has 1 month for remedy. The re-submitted MIT plan is evaluated again in the same manner, the payment of the deposit bound to this milestone is on hold.

7.5 Documentation

7.5.1 The Buyer's Drawings

Coil design drawings provided by the Buyer will be listed in the Annex. All dimensions refer to room temperature (20° C) conditions. Dimensional characteristics including tolerances and insulation builds are given in the drawings (details in 5.11). For the G-10 fillers some geometry is only defined in the model using STP files, available on request.

7.5.2 Seller's Drawings

Seller shall prepare manufacturing and tooling drawings as required to complete the fabrication. The manufacturing and tooling drawings shall be submitted to the Buyer for review and approval prior to use.

7.6 Codes and standards

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.

7.7 Classification from the perspective of radiation and environmental impacts

The subject of this tender does not contain any radioactive substances or sources of ionizing radiation. The final product does not contain substances endangering the environment, but the processes during its manufacture may require precautions to prevent contamination of the environment and health risks to the operators (e.g. process of conductor priming and VPI process).

8 Quality Assurance

8.1 QA plan

Seller shall submit a Quality Assurance (QA) plan describing the specific quality assurance and quality control procedures and practices, including special process training and qualifications, which will be in force to meet the requirements of this specification. The QA plan and any revisions require review and approval by the Buyer prior to the start of design or manufacturing of the equipment under this specification.

8.2 Inspection, Surveillance and Audit

Seller 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 the Buyer. The Buyer reserves the right to designate selected manufacturing, inspection and/or test operations as mandatory Witness or Hold points, as mentioned above in the subsection 7.4.

In addition, due to the critical nature of these components, authorized representatives of the Buyer could come to visit and check the production process on site except agreed Witness or Hold points schedule. Such visits will be announced by the Buyer to the Seller at least five working days in advance. This Buyer representative will inform the Buyer of progress and will have the authority to halt the fabrication process until issues are resolved, if some are identified.

Additionally, the video of the whole manufacturing process should be recorded and provided to the Buyer at the end of the manufacturing process, including all tests on the Seller side. The Buyer reserves the right to ask for the recorded parts during the manufacturing process. Moreover, the actual video should be accessible online.

8.3 Seller's Quality Assurance Program

Seller shall establish and maintain an effective Quality Assurance Program to assure that Seller's work meets the required level of quality and is performed in accordance with contractual requirements. Seller's quality assurance 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. The Buyer will conduct an on-site pre-award assessment of the Seller's Quality Assurance Program and capabilities of meeting the requirements of this specification.

8.4 Submittal of Quality Assurance Program Description

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

8.5 Inspection and Test Procedures

Inspections and tests shall be performed in accordance with the MIT plan (section 7.4) with approved (separate or incorporated) procedures referencing criteria for acceptance or rejection. Adequate records shall be maintained and available for the Buyer review.

8.6 Document Traceability and Records

The Seller 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 7.4 and 8.8) and relevant data such as materials certifications, material test reports, inspection reports, discrepancy reports, etc. This information shall be complete and legible and validated by responsible personnel and shall be traceable to subject items.

8.7 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.

8.8 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.

8.9 Witness/Hold Points and Notification of the Buyer in Advance

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

- When welding / brazing / soldering qualifications are specified, welding / brazing / soldering must not occur until all required welding documentation is submitted and approved by the Buyer.

- When a Release for Shipment form is specified, shipment must not be made until the shipping release form is signed and returned by the Buyer.

Table 8-1 - List of hold/witness points

	Activity subjected to the hold/witness point	**Action required**
	Start of each coil winding process	
	Coil´s each interim checks before VPI	
	Each coil´s FATs	
	Terminal brazing/ coolant feeder brazing/ brazing qualification?	

8.10 Non-Conformance and Corrective Actions

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

8.11 Configuration Control

Subcontractor shall completely document the configuration of delivered end items or services, using drawing revisions, specification revisions, unique part numbers, or other suitable means.

8.12 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 National Metrology Institute (NMI) which is a member of International Bureau of Weights and Measures (BIPM). 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.

8.13 Performance and Documentation of Inspections and Tests

Each item to be delivered to the Buyer shall be inspected and tested by Seller to verify that they meet the Buyer's requirements. Results shall be documented and reported to the Buyer.

8.14 The Buyer Receiving/Inspection

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

8.15 Process History

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

8.15.1 Material Certification

Manufacturer’s Certified Material Test Reports (CMTRs) showing relevant chemical, mechanical and electrical properties of materials used, where applicable, shall be submitted to the Buyer. Certifications for the insulation epoxy, copper material (conductor, pipes, etc.), braze material, solder and flux 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 the Buyer when the Seller approves the material for use (start of the job).

8.15.2 Fabrication Process Reports

Curing waveforms…, temperature, humidity

8.15.3 Inspection & Test Reports

The completed MIT form, 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 Seller personnel prior to submittal to the Buyer.

8.15.4 Non-conformance Reports

Signed copies of any non-conformance reports generated per section 7.10 shall be included in the process history.

8.15.5 Shipping Release

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

8.16 Changes of the Buyer Approved Documents

Revisions or changes by Seller to documents approved by the Buyer shall be reviewed and approved by the Buyer prior to use.

8.17 Seller’s Responsibility for Conformance and Flowdown of Requirements to Sub-tier Suppliers

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

9 Annexes

drawings, …