Tokamak Physics Experiment (TPX) Toroidal Field Magnet Final Report

LLNL Contact: Lawrence R. Pedrotti, Toroidal Field Technical Contract Manager

Babcock & Wilcox: R.R. Batchelder, R. R. Smith, R. F. Ryan, P. Conde,
T. Antaya, T.A. Brandsberg, H. Bell, J. Maloney, W. Young, C. Weber,
D. N. Alger, W. F. Bensiek, N. K. Albritton, R. deKoven, K. E. Grut,
D. Hoffman, B. Holt, E. Hooks, X. Huang, D. Johanson, R. Kunz, Y. Lvovsky,
G. Markham, J. Meissner, P. Rackov, C. Rey, D. Stutski, J. VandeBogart,
R. Whitfield, B. Wilmer, M. Xu, W. Young

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TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE

Contract B235308

SDRL 15

System Design Description

TPX-SDD-013

August 18, 1995

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Babcock & Wilcox
Accelerator & Magnet Systems
PO Box 785
Mt. Athos Road
Lynchburg, VA 24505

Approved for Submittal by:
C.M. Weber, TPX Project Mgr.

PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**TOROIDAL FIELD MAGNET
SYSTEM DESIGN DESCRIPTION**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-SDD-013
REVISION 0**

Prepared for: the University of California
Lawrence Livermore National Laboratory
Subcontract B235308, SDRL 15

Prepared by: the Babcock & Wilcox Company
NNFD, Accelerator and Magnet Systems
Mt. Athos Road, Lynchburg, VA 24505

The original document is on file at B&W.

It was compiled and signed by:	R.R. Batchelder, B&W Systems Engineering
It was approved and signed by:	T.A. Antaya, B&W Chief Design Engineer
It was approved and signed by:	R.J. Kunz, B&W Systems Engrg Manager
It was approved and signed by:	R.F. Ryan, B&W Manufacturing Engrg Manager
It was approved and signed by:	C.M. Weber, B&W TPX Project Manager
It was approved and signed by:	G.A. Deis, LLNL Magnet WBS Manager
It was approved and signed by:	W. T. Reiersen, TPX Systems Engineering Manager
It was approved and signed by:	J.C. Sinnis, TPX Project Engineer
It was approved and signed by:	G.H. Neilson, TPX Physics Manager
It was approved and signed by:	J.A. Schmidt, TPX Project Director

SIGNATURE SHEET

Compiled by:
R.R. Batchelder, B&W Systems Engineering

Approved by:
T.A. Antaya, B&W Chief Design Engineer

Approved by:
R.J. Kunz, B&W Systems Engrg. Manager

Approved by:
R.F. Ryan, B&W Mfg. Engrg. Manager

Approved by:
C.M. Weber, B&W TPX Project Manager

Approved by:
G.A. Deis, LLNL Magnet WBS Manager

Approved by:
W. T. Reiersen, TPX Systems Engineering

Approved by:
J.C. Sinnis, TPX Project Engineer

Approved by:
G.H. Neilson, TPX Physics Manager

Approved by:
J.A. Schmidt, TPX Project Director

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FORWARD

This System Design Description, prepared in accordance with the TPX Project Management Plan, §13.1.4, provides a summary of TF Magnet System design features at the conclusion of Phase I, Preliminary Design and Manufacturing Research. The document includes the analytical and experimental bases for the design, and plans for implementation in final design, manufacturing, test, and magnet integration into the tokamak. Requirements for operation and maintenance are outlined, and references to sources of additional information are provided.

F-1 TF Magnet System Function and Configuration

The function of the Toroidal Field (TF) Magnet System is to provide the toroidal field necessary to magnetically confine the TPX plasma.

The TF Magnet System is comprised of three subsystems: the TF Magnet, an array of 16 superconducting coils spaced 22.5° apart and housed in a steel structure (Figure F-1); TF Local Instrumentation and Control, which provides quench detection and engineering data; and TF Bus and Leads, which conduct dc power from the magnet power supply to the magnet.

Figure F-2 shows the functional relationships between the TF magnet and interfacing systems. The magnet rests on the Tokamak Support Structure (WBS 16), supports the Poloidal Field (PF) coils (WBS 14) and Field Error Correction Coils (WBS 19), and accommodates the Vacuum Vessel (WBS 12) and Vacuum Pumping ducts (WBS 34) which penetrate the TF assembly. In addition, the TF Magnet is housed within the Cryostat (WBS 15), receives liquid helium coolant from the Cryogenic Equipment (WBS 72), receives power from the TF Power System (WBS 42), and exchanges data with Central I&C (WBS 61).

The TF magnet is delivered as identical two-coil octants, which are combined into quadrants for assembly into the tokamak (WBS 17). The bolted octant joints enable precise alignment at assembly, and provide electrical breaks to reduce the effects of eddy currents during field transients. TF magnet assembly is completed with connection of power and instrumentation leads and cryogenic lines in the lead boxes.

Figure F-1 TF Magnet Configuration

Figure F-2 TF Magnet Functional Relationships

F-2 Requirements Flow-down and Verification

The TF Magnet System Requirements Document (TPX-SPEC-013-0001) defines the performance, design, and quality verification requirements of the system. This document contains requirements flowed down from the TPX General Requirements Document (TPX-RQMTS-GRD) through the Tokamak Systems Requirements Document (TPX-RQMTS-SRD) and project standards, as shown in Figure F-3. Interfaces with other TPX systems will be defined by primary Interface Control Documents.

Requirements for the magnet coil, the superconductors, Local I&C, Bus and Leads, and critical coil manufacturing equipment are flowed down from the TF Magnet System Requirements Document through subsystem specifications, as shown in Figure F-4. The relationships between the subsystems will be documented in secondary ICDs.

Programmatic requirements governing implementation and verification of the design flow from the TPX Project Management Plan, through functional plans, to corresponding plans and documentation at the TF magnet level, as shown in Figure F-5. Preliminary plans have been prepared for magnet final design, manufacturing and test during Phase I, TF Magnet Preliminary Design, and these will be extended in Phase II. Figure F-6 is a summary schedule of magnet development activities leading to TPX first plasma in July, 2001.

Figure F-3 Requirements Flow-Down to TF Magnet

Figure F-4 Requirements Flow-Down from TF Magnet System

Figure F-5 Programmatic Requirements Flow-Down

Figure F-6 TF Magnet Summary Schedule

F-3 Performance and Operational Requirements

In steady state operation with a current of 33.5 kA, the TF magnet shall provide a minimum field strength of 4.0 T in the tokamak midplane at a major radius of 2.25 m:

- for the full flexibility space of GRD Section 1.2,
- with source rates of 1.2×10^{17} DD neutrons/sec and 3.6×10^{15} DT neutrons/sec, and
- with eddy current heat loads associated with plasma vertical position control.

The TF magnet shall also accommodate 1 sec of operation with a DT plasma (with a maximum fusion power of 15 MW and a corresponding DT source rate of 5.3×10^{18} neutrons/sec), obtained by injecting tritium into a fully formed and heated D plasma.

The TF magnet shall accommodate the transients (plasma startup, current ramps, and beta changes) associated with the HC and LC scenarios per GRD Section 1.1. The TF magnet shall also accommodate plasma disruptions per GRD Section 1.10 without quenching.

The TF magnet shall be designed for four quadrant operation, i.e.

- the toroidal field will be bi-directional and
- plasma current may be in the same direction as, and in the opposite direction to the toroidal field.

The peak-to-average TF ripple shall be $\leq 0.4\%$ over the entire plasma cross section.

The radial components of magnetic field on the plasma surface due to the non-axisymmetric effects of TF coil misalignment, TF coil leads and cross-overs, TF magnetic materials, and the TF bus shall not exceed the following values, allocated from the total allowable field error through the Tokamak SRD:

$$\delta B_{r\ 1,1} \leq \text{TBD Gauss}$$

$$\delta B_{r\ 2,1} \leq 0.32 \text{ Gauss}$$

$$\delta B_{r\ m,1} \leq 0.64 \text{ Gauss, } m = 1, 3, 4$$

$$\delta B_{r\ 4,2} \leq 0.64 \text{ Gauss}$$

$$\delta B_{r\ m,2} \leq 1.28 \text{ Gauss, } m = 3, 5$$

where $\delta B_{r\ m,n}$ are the Fourier components of radial field strength with poloidal harmonic number "m" and toroidal harmonic number "n".

TF Local I&C shall detect a quench in the magnet or the bus in sufficient time to initiate a coil dump without exceeding the voltage or temperature limits prescribed in the TPX Structural and Cryogenic Design Criteria Document.

Each octant of the TF magnet shall be electrically isolated from all other assemblies, and grounded with a single-point ground connection. When isolated from ground, each octant shall demonstrate a 1 kV standoff voltage from all other octants and systems.

The TF magnet and bus shall be capable of being cooled down from room temperature to operating temperature in 10 days, and of being warmed up from operating temperature to room temperature in 5 days. The magnet shall recover to operating temperature following a coil quench in 12 hours.

The TF magnet shall be designed for a 10-year operating life, with up to 2×10^6 sec of D operation and 5×10^6 sec of total operation, and with the following events:

- 30,000 plasma pulses
- 15,000 plasma disruptions
- 6,000 TF charge-discharge cycles (which includes cycling required for GDC)
- 300 cool-down / warm-up cycles between room temperature and operating temperature
- 50 quenches.

All materials used in the TF magnet, except for the conductor sheath, shall have a relative magnetic permeability less than 1.02. After exposure to a total lifetime neutron production of 4×10^{22} DD neutrons and 8×10^{20} DT neutrons, magnet materials shall not exceed Class A low level waste limits as defined in 10 CFR 61 regulations.

F-4 RAM Requirements

The availability of the TF Magnet System shall be not less than 97.0%. Availability is defined as $100\% \times (1 - N)$, where N is the ratio of the number of shots in which the TF Magnet System failed to meet its performance requirements to the number of shots that could be achieved in an operational period. Delays due to low probability events, such as a TF coil replacement, shall not be included in availability verification.

The shot reliability of the TF Magnet System, defined as the probability of TF Magnet System operation without malfunction for the duration of a shot, shall be not less than 0.9958.

Maintainability of the TF Magnet System shall be consistent with the foregoing availability requirement, applied to components accessible outside the TF magnet assembly. TF magnet components within the cryostat, including connections in the magnet lead box, shall be accessible for disassembly and repair within two weeks following tokamak shutdown. The TF magnet shall be capable of physical disassembly to permit replacement of a failed coil, following a shutdown period of up to one year during which activated in-vessel components are remotely removed.

TF Local I&C shall require periodic calibration and maintenance at an interval of not less than six months. Scheduled maintenance for any other purpose shall not exceed one week per three operating weeks averaged over a 32 week run period.

Provisions for recovery shall be made for every failure mode which

- has a reasonable probability of occurrence ($P \geq 10^{-4}$) over the life of the device or
- has a low probability of occurrence ($10^{-4} > P \geq 10^{-6}$) over the life of the device and no exemption from the Project based on cost/risk/benefit considerations

and which, directly or indirectly, would compromise the required operational capability of the device and facility.

The foregoing reliability, availability, and maintainability criteria do not apply after injecting tritium into the plasma.

1. TF SYSTEM DESIGN

TPX is an advanced diverted tokamak with a large operating space, in which the TF magnet system provides the following critical functions:

- Primary plasma guide and confinement field-- the magnetic reference for the rest of the system
- Mechanical support structure for the Central Solenoid, outer PF coils, Field Error Correction Coils, and much of the cryogenics distribution system
- Through porting-- all vacuum, diagnostic and plasma heating components must pass through the TF structure
- Capability for long pulse and (limited) DT operation

Much future fundamental confined plasma science will come from TPX. The TF magnet system must be highly reliable and available to ensure that experiments are not missed or time lost in repairs. The TF system design is therefore a robust balance of design requirements and design constraints. The most significant design drivers are:

- Structural integrity -- the TF nose must wedge under all conditions, and cyclic motion (ratcheting of the eddy current break and the TF structure) must be controlled
- Thermal stability -- space is tight for shielding and cooling
- Insulation integrity -- conduit shear stress mitigation
- Field precision -- design symmetry, fabrication tolerances, alignment
- Accessibility for maintenance -- competition between structural and electrical functions in the lead box.

In order to respond to this set of design drivers, while at the same time making the system economically buildable, a number of significant adjustments have been made to the CDR baseline TF system design, including:

- An all-bolted, wedged TF structure with 16 full size equatorial ports
- Inconel 625 welding of the main case components to minimize deformation and ferritic inclusions
- A case cooling configuration with channels in the case side walls and intercoil structure that simultaneously meets requirements, does not compromise the structure and is very buildable
- Coil insulation with 3D reinforcement to mitigate shear stress, as well as kapton barriers that define conduit slip planes
- An integrated alignment plan (coil and case fabrication, assembly and alignment) for achieving as-built tolerances that meet the TF magnet system "A-Spec" field error requirements
- A lead insulation concept that permits an open lead box design
- Roll-formed winding pack turn transitions that minimize winding setup changes
- Eight identical octants and 16 identical coils.

Perhaps the best illustration of the impact of that these changes has made on the manufacturability and cost of the TF magnet system is to compare the CDR parts heirarchy with that of the present design, as shown in Figure 1.0-1. As can be seen, the number of unique components in the TF system has been significantly reduced, while meeting the design requirements and reducing the manufacturing costs, as will be demonstrated.

CDR PARTS HEIRARCHY:

- 2 TYPES OF QUADRANT
- 4 TYPES OF OCTANT
- 4 TYPES OF COIL
- 4 TYPES OF CONNECTING FACE
- 1 TYPE OF ICS

HAS BEEN SIMPLIFIED TO:

- 1 TYPE OF QUADRANT
- 1 TYPE OF OCTANT
- 1 TYPE OF COIL
- 2 TYPES OF CONNECTING FACE
- 1 TYPE OF ICS

Figure 1.0-1 Present TF Magnet Component Heirarchy Compared with CDR

1.1 TF Conductor (WBS 132)

Each of the sixteen TF coils is fabricated from Nb₃Sn superconductor, cooled with supercritical helium in a cable-in-conduit configuration derived from the US-DPC. There are 84 turns per coil, arranged in 12 layers of 7 turns each. Each coil is wound from a single length of conductor approximately 1,008 meters long. The conductor cross section is shown in Figure 1.1-1

Figure 1.1-1 TF Conductor Cross Section

1.1.1 Strand

The TF conductor contains 486 multi-filament strands of Nb₃Sn, produced by either a bronze composite or Nb-Sn "jelly roll" method. The characteristics of the strand are as follows:

Diameter	0.78±0.01 mm
Critical current*	148 A
Cu/SC ratio	2.5±0.2
Hysteresis loss†	<550 kJ/m ³
Resistivity at 20 K	<0.2 nΩm
Coating	0.5 - 1.5 mm, Cr or Nb
Filament twist pitch	9±1 mm, RH

* after reaction with a 9 T field perpendicular to the conductor, 4.2 K, $E = 1 \times 10^{-5}$ V/m

† Hysteresis measured in 3 T : 0 : -3 T : 0 : 3 T cycle

1.1.2 Cabling

The 486 TF strands are cabled in a 3 x 3 x 3 x 3 x 6 fully transposed configuration, with the following characteristics:

Length	1,100 m
Twist pitch	RH (all stages)
Stage 1 (3 strands)	40±4 mm
Stage 2 (3 x Stage 1)	80±8 mm
Stage 3 (3 x Stage 2)	160±16 mm
Stage 4 (3 x Stage 3)	240±24 mm
Stage 5 (6 x Stage 4)	360±36 mm
Over-wrap	304 stainless steel tape
Thickness	0.05 mm
Width	19 - 40 mm
Overlap	50%
Sensor leads	2 Fiber optic, 6 voltage taps co-wound per Figure 1.1-2
Lead diameter	0.125 mm

Figure 1.1-2 Sensor Lead Positions

1.1.3 Conduit

Incoloy 908 is chosen for the conduit material since its contraction from the reaction temperature of 700 °C to operation at 4 K is very close to that of the Nb₃Sn, minimizing J_c degradation; and Incoloy 908 has very good fatigue properties in thin sections.

The conduit will be fabricated either by rolling I-908 strip around the cable and welding a continuous longitudinal seam; or by drawing the cable through extruded or welded circular tube sections, which are butt-welded together and drawn to final shape. The dimensions of the finished conduit are as shown in Figure 1.1-1. The conduit will have an external surface finish of 125 μin. for compatibility with the Kapton insulation film.

In order to achieve sufficient accuracy in coil forming, the yield strength of the finished conduit material must be extremely uniform, and the cross section must be symmetrical to prevent twist during bending. Tolerances of $\pm 5\%$ on yield strength, and ± 0.001 in. on the symmetry of the tube walls are recommended.

I-908 is susceptible to Stress Accelerated Grain Boundary Oxidation (SAGBO), an intergranular cracking phenomena that would significantly lower the fatigue resistance of the conduit or result in catastrophic failure. SAGBO is well understood as a threshold phenomena, and furnace allowables can be defined to exclude it. In order for SAGBO to occur in the Incoloy 908 conduit during the high temperature Nb₃Sn reaction cycle, one must have three ingredients: temperature, residual strain and oxygen. It has been determined that if the oxygen concentration in the furnace surrounding the sample is less than 0.1 ppm, when in the critical temperature range ($\sim 700^\circ\text{C}$), then SAGBO will not occur, independent of the stress state of the Incoloy 908 material. Conduit formed into the TF coil shape will have significant residual strain, hence the oxygen concentration both inside and outside the conduit will be held significantly below the 0.1 ppm level during the heat treatment process to suppress SAGBO cracking.

Prior to delivery, the conduit will be tested to the maximum expected internal quench pressure of approximately 90 atm., and helium leak tested. Finished conductor will be delivered on a spool approximately 2.5 m in diameter and 2.0 m high, which carries the 1,100-m conductor length in 225 turns, or 4 full layers and a partial layer.

1.1.4 TF Conductor Performance

The estimated TF conductor performance, for the baseline hydraulic flow parameters (3.91 g/s, 3 atm return), is summarized in Table 1.1-1. The actual maximum field at the conductor varies over the TPX flexibility space from 8.25 T to 8.34 T, and is bounded in the table.

Table 1.1-1 Nominal TF Conductor Performance

<i>Parameter</i>	<i>Units</i>	<i>Value</i>
B _{maxTF}	T	8.4
T _{b, nom}	K	5.0
Superconductor strain	%	<0.3
I _c (8.3 T, 5 K)	kA	78.9
$\Delta T_{\text{headroom}}$	k	3.0
f _{critical}		0.56
h _{tr}	W/m ² -K	>800
RRR		75

1.1.5 TF Bus Conductor

The TF bus will be constructed of NbTi superconductor in a circular stainless steel sheath, as shown in Figure 1.1-3.

Figure 1.1-3 TF Bus Conductor Cross Section

1.2 TF Magnet (WBS 133)

The TPX is designed to run double-null, high-beta and high-bootstrap-fraction plasmas, as well as single-null plasmas at full current. Because the TPX mission includes the achievement of steady-state and extremely long pulse operation at full parameters, the use of superconducting coils was an obvious choice for the magnet system. The TF system is designed for full four-quadrant operation, with the plasma current and toroidal field in either clockwise or counter-clockwise directions in the coordinate system of Figure 1.2-1.

The toroidal field system consists of sixteen coils in cases with welded intercoil structures. Each coil consists of 12 layers of cable-in-conduit-conductor (CICC), with a total of 84 turns in each winding pack. TF magnet characteristics are listed in Table 1.2-1.

1-7

Table 1.2-1 TF Magnet Characteristics

<i>Parameter</i>	<i>Units</i>	<i>Value</i>
Maximum field	T	8.4
Maximum Current	kA	33.5
Peak dump voltage	kV	±7.5
Number of turns/layer		7
Number of layers		12
Number of coils		16
Total number of turns		1344
Stored Energy	GJ	1.06
Conductor length per coil -	km	1.05
Total conductor length	km	16.93

The TF coils are wound continuously without joints, in layers with an out-to-in and in-to-out winding sequence. While the pancakes are wound, coated metallic spacers are inserted as place-holders for the magnet insulation, and helium coolant stubs are welded in place. The entire winding pack is then reacted to form the Nb₃Sn superconductor.

After reaction, the turns of the coil are separated and insulated with two half-lapped layers of 0.025-mm. Kapton tape, followed by one half-lapped layer of 0.36-mm 3D S2-glass tape. This redundant insulation system improves reliability, while providing a conduit slip interface and mitigating insulation shear stress [13-950301-BW-TAntaya-01]. The insulated turns spiral into a mold for vacuum pressure impregnation. After impregnation, the winding pack is removed from the VPI mold, wrapped with a layer of 3D S2 glass tape, followed by an aluminum crepe shield wrap, and then overwrapped with another layer of S2-glass tape. The winding pack is then returned to the VPI mold, and the ground plane is vacuum impregnated. This additional step ensures the integrity of the ground plane, as well as ensuring that the critical first VPI step has minimal barriers to full penetration of the epoxy.

The TF structure consists of welded 316LN coil cases with thickened noses at the inside leg to support centering loads in wedging, and an outboard intercoil structure between the coils to support the toroidal load and over-turning moments. A common box at the top of the outboard structure encloses the leads from both octant coils. The TF octant structure is assembled by bringing together the inboard leg sub-assembly, two coil case assemblies and the intercoil structure and aligning them in a welding fixture. All components are welded in place using Inconel 625 filler material. Inconel 625 exhibits only 30 to 50% of typical 316 weld distortion, eliminating elaborate preparations to ensure against weld cracking, and providing a fully martensitic weld. The welded TF structure is annealed, machined and alignment fiducials installed.

The insulated coil is placed in the coil case, and after verification of coil placement within the case, the coil is secured with partial potting using a glass-filled epoxy. The case side/bolted joint sub-assembly will be installed and welded, and the balance of the case cavity filled with epoxy. The use of a filled resin lowers the thermal contraction coefficient of the epoxy to that of the case material, ensuring that the full case compression of the winding pack is achieved when cooled to LHe temperatures.

Final alignment and machining of the octant structure is performed after the coils have been installed. Two octant assemblies of two TF coils apiece, along with other tokamak components, are then joined at the intercoil structure parting plane with an insulated break joint, to form a 90° module. Insulating sheets are inserted in the TF coil noses between

every two coil octant. Compression is ensured in the insulation through bolted flanges at the top and bottom of the TF inside legs. Stresses in the winding packs and cases have been calculated for in-plane and out-of-plane loads at most plasma conditions, as described in Section 2.2.2. The highest stresses occur in the port region, where the intercoil structure is constrained by the need for large openings between each TF coil.

The leads and crossovers use a copper splice block concept developed at LLNL, described in Section 2.3.7. Each lead is hydraulically connected to the splice structure, the conductor is soldered to the splice body, and sensors are extracted from the opposite end. Interconnects are made by bolting two splice blocks together. The bolting surfaces are slightly curved, to be flattened during bolting to insure good contact and minimize the resistance of the joint. In Section 2.3.7, a "praying hands" configuration is shown, but a "hand shake" orientation will be used in all TF locations with the exception of one type of coil-to-bus joint.

Quench detection must occur within an adequate time to ensure that the energy stored in the coil can be dumped without exceeding a maximum hot spot temperature of 150 K. Calculations reported in Section 2.2.3 indicate that quench detection within 1.6 sec of the quench should be sufficient to provide an adequate safety margin. The quench detection system will include three independent systems to provide fast and reliable quench detection: internal co-wound voltage taps with a 10:1 signal-to-noise ratio, internal fiber optic temperature sensors, and external flowmeters [1314-950628-MIT-SSmith-01].

1.2.1 TF Coil

1.2.1.1 Coil Geometry

The TF coil assembly is shown in Figure 1.2-2. Each of the sixteen TF coils is 4.9 m high and 3.1 m wide, and is approximately "Dee" shaped; each coil winding pack weighs 3.5 tons. The Nb₃Sn superconductor is cooled with supercritical helium in a cable-in-conduit-conductor (CICC) configuration. Connections to the helium headers are made on the low field side of the coil at the layer-to-layer crossovers, and the helium traverses one double layer before exiting the coil. The hydraulic path length of each cooling loop is about 176 m. The insulator, filters, instrumentation, and headers for the cooling lines are located at the top of the intercoil structure between coil pairs.

There are no joints at the transitions between coil layers, which is accomplished by winding the coil radially inward on the first layer, then backwinding radially outward on the next layer and repeating the process until all 12 layers are obtained, as shown in Figure 1.2-3. A three roll bender is used to bend the conductor to the correct radius, as described in Section 3.3.2.1.

The transitions between coil layers, and the transitions from layer to layer are located at the top of the coil in an angular arc of 45°, as shown in Figure 1.2-4. In the adjacent layer, there must be a turn shift to accommodate the layer-to-layer conduit transition. There are two types of turn shift, and these occur just prior to layer transitions. All bends in the plane of the layer are roll formed, which permits the winding process to continue without interruption. Locating all transitions in the top of the coil provides a compact, rectangular conductor array with no voids in the inner and outer legs of the coil, and with smooth, gradual bends in the transition region.

Figure 1.2-2 TF coil assembly (Dwg D-1335000)

THE WINDING PACK PATH IS DEFINED AS THE CICC CENTERLINE.

THE RADIAL DIMENSIONS ARE TO THE INNER AND OUTER TURNS. THE DISTANCE BETWEEN EACH TURN TO TURN IS 1.134° .

THE OUT-TO-IN AND IN-TO-OUT PANCAKES ARE IDENTICAL EXCEPT FOR THE UPPER REGION WHERE THE PANCAKE TURNS AND PANCAKE TO PANCAKE TRANSITIONS OCCUR.

Figure 1.2-4 TF Conduit Winding Path (Dwg. C-1335101)

The aggregate effect of the transition area is to make the winding pack effectively 8 turns wide at the top of the coil. Prior to the first VPI, void spaces created by the turn shifts and layer transitions will be filled with contoured mats of 3D S2-glass fibers. Upon impregnation, these regions will become composites with the same structural properties as the insulation over-wrapping the conduits.

Lead spurs are not included in the winding pack to anchor the leads. The addition of lead spurs would complicate an already complex lead area (leads, ground wrap, helium stubs, filters, flow meters, splice joints), and the required restraints were easily incorporated in the support structures for leads and interconnections in the lead box assembly.

1.2.1.2 Coil Leads

In the TF conceptual design, there were four coil types, each having different lead configurations, as indicated in Figure 1.0-1. Also, due to concern for electrical discharges in the lead area from poor vacuum (a discharge is easily ignited in a partial pressure of helium, the most likely contaminant gas in the vacuum surrounding the leads), it was planned that the coil and lead area be isolated in a separate high vacuum, with the leads exiting the sealed lead box through vacuum feedthroughs. Finally, owing to the brittleness of Nb₃Sn after reaction, the minimum bend radii of the leads were set rather large to avoid over-straining the conductor, resulting in large loops of conductor, 3D bends, and very difficult to support.

As a consequence, the lead box area would be a likely trouble spot in TF system operation. The territory surrounding the TF lead box is crowded: the upper FECC, PF-6U, cryo distribution lines and the upper vacuum pumping system all reside nearby. The Failure Mode Effects and Criticality Analysis in Section 2.2.6 supports this view -- two of the top five critical failure modes involve lead box components. The history of large magnet operations highlights lead fabrication and maintenance difficulties.

Design goals for the lead area of the TF coils are:

- 16 identical coils -- reduce coil cost including tooling, provide interchangeability
- Shorten the leads where possible to minimize bias lengths, electromagnetic loads and extra current loops
- Open the case to the cryostat -- the extra set of vacuum feed-throughs increase magnet failure risk, and coil operation with poor cryostat vacuum is impossible
- Design a sliding insulator support for the lead outlet from the case
- Insulate all exposed biased surfaces to eliminate the possibility of electrical discharge in the lead area
- Provide sufficient space for multiple insulated lead supports, including coil/lead transition areas.
- Design a bolted case structure if structural analysis indicated that welding was not required.
- Lower the splices to simplify support, and use only 2D bends, with 7.5 in. and 9.0 in. minimum bend radii in the hard and easy directions respectively.
- Move the electrical isolators as close to the helium stubs as is feasible to minimize exposed conducting surfaces in the lead area.

Of particular importance, given the density and complexity of the components in the lead area, is adequate electrical insulation to avoid breakdown during normal and abnormal

events, either of which would be catastrophic for the TF magnet system. The lead electrical design paradigm is as follows:

- Most likely fault -- partial vacuum arc discharge in helium
- Paschen minimum for He ~170 V -- hence keep all exposed voltages below this threshold, all exposed conductors are insulated
- A good insulation choice-- a build-up kapton tape
- Insulators are good secondary electron emitters, particularly in a strong magnetic field where current densities are concentrated, so insulation should be metal foil taped
- The metal foil should be grounded to control the peak electrical fields
- The metal foil serves a secondary function-- mechanical protection for the insulation.

The overall arrangement of the coil lead area, looking down from the top of the lead box, is shown in Figure 1.2-5. The same area, but looking in from the side, is shown in Figure 1.2-6. In both views, the top and front to the chimney has been removed, as are the lead supports.

A typical coil-manifold helium feed circuit is shown in Figure 1.2-7. The lead support system is shown in Figure 1.2-8, while a typical insulated lead support is shown in Figure 1.2-9. The corresponding hydraulic circuit for the components in one octant is shown in Figure 1.2-10.

In order to better understand the hardware shown in Figures 1.2-5 through 1.2-9, please refer to the schematic diagram in Figure 1.2-10. The octant coil-to-coil splice joint is visible in the center of Figure 1.2-5. The upper FECC is seen to surround the chimney box, while the LHe feed and He return loops are in front of the box. The filter-flowmeter lines from the coil helium return lines are also seen. In Figure 1.2-6 the coil helium feed and return lines, and the isolation joints lines are more easily seen.

A typical LHe feed assembly is shown in Figure 1.2-7. Each assembly includes an electrical isolator (located near the outlet to minimize exposed biased conducting surfaces), a flow meter (type presently undefined) and a filter. All such units are identical (in dimensions between elements) for all coils, and will be built and tested prior to installation, with the final operation to connect to coils being closure welds. In Phase II, we plan to qualify a connector design for use in this application, permitting removal and repair of cryogenic components without cutting and welding. With all assemblies the same, the number of required spares will be minimized.

All leads will be Kapton-taped and metal foil-covered to eliminate exposed high voltage surfaces in the lead box, obviating the need for a separate vacuum for lead box components. For redundancy, all lead supports and feed-throughs will also be made with insulating materials. The lead support arrangement is shown in Figure 1.2-7. A set of struts are bolted to lead box case components. Lead and splice joint hangers are hung from the supports to anchor the current carrying surfaces in the lead box. The entire support assembly can be removed by personnel situated outside the lead box. A typical lead hanger is shown in Figure 1.2-9. The hanger is assembled around the lead, permitting disassembly at will to repair lead box components. The lead capture fitting is made with wedged G-10 pieces. Lead hangers are situated as needed to support the forces on the coil leads.

Figure 1.2-5. Lead Box Top View

Figure 1.2-6. Lead Box Front View

Figure 1.2-7 Typical LHe Feed Assembly (Dwg. C-1336110)

Figure 1.2-8 Lead Support Structure

Figure 1.2-9 Typical Lead Hanger Assembly

Figure 1.2-10 TF Octant Hydraulic Circuit (Dwg. C-1333102)

1.2.1.3 Coil Hydraulics

Figure 1.2-10 shows the cooling paths through the coils in an octant, with all other octants being the same. Supercritical helium is introduced into the layers on the outside (low field side) of the coil. The helium traverses through the layer to the transition at the high field side and then spirals out through the adjacent layer. Each double layer is one cooling path. The location of each coolant inlet/outlet connector is at the low field side layer-to-layer transition, just after the coil top. These helium stubs form true hydraulic "Tees" with divided flow at the inlet and outlet. At the ends of the leads there are also helium outlets for the coil leads, and the splice joint has a separate helium feed and return.

The intercoil and case structures are cooled with the return flow from the coils. The configuration of the case cooling lines is described in Section 1.2.2.4.

1.2.1.4 Coil Insulation

Coil insulation was identified as a critical magnet system design driver, but not for the reasons one generally considers critical in the selection of coil insulation. The maximum voltage experienced by a TF coil is 7.5 kV. The TF coil voltage holding requirement of $16 \text{ kV} = 2(7.5 + 1)$ is well within the capabilities of epoxy composite insulation systems. The main reason for the present insulation system for the TF coils is structural -- shear stress and excessive tension in the winding pack.

The CDR baseline insulation consisted of S2 glass tape turn insulation, classical S2 glass fiber bundles for corner roving, and G-10 turn-to-turn and layer-to-layer barriers, following the insulation scheme employed on the US-DPC coil. However, anisotropy in the thermal contraction coefficient of the epoxy composite led to predicted shear stresses in the 40-70 MPa range that exceeded allowables upon cool-down only, and were increased under cool-down plus electromagnetic loads. In addition, the TF winding pack showed considerable tension that case compression alone would not mitigate.

TPX adopted the ITER criterion of not allowing tension in the winding pack insulation. To accomplish this, the TF coils are installed in 316LN cases. Since 316LN has a higher thermal contraction coefficient than Incoloy 908, the winding pack is compressed during cool-down. The fundamental problem is that in the direction perpendicular to the glass fiber plane, the composite exhibits epoxy-like properties -- a significantly lower modulus and substantially higher thermal contraction rate.

The new baseline uses S2 glass tapes with a 3D weave, 3D S2 glass corner fillers, and 3D S2 glass mats to fill transition spaces. In 3D preforms, some fraction of the warp fibers extend into other woven layers, thereby adding glass properties in the through-thickness direction. At the present time, large scale testing is in progress to verify that winding pack insulation systems based on these materials will meet TPX performance requirements. In the interim, we are using this approach based on supporting analysis, as presented in Section 2.2.2.

The baseline insulation system was shown previously in Figure 1.2-2. The turn insulation will be installed after the Nb₃Sn reaction step. The details of the turn insulation installation are summarized in Section 3.3.2.3. The reacted winding pack is inverted, and unwound a turn at a time into the VPI fixture, to allow the addition of the insulation. Some dimensional changes will occur during the thermal reaction cycle. In order to re-establish the coil shape

prior to vacuum impregnation, the VPI fixture will be used as a precise form to redefine the coil shape.

There are two VPI steps -- winding pack impregnation and ground plane impregnation. The same form is used for both steps. For the first step, teflon spacers will be inserted into the form to define the outside dimensions of the coil, as well as making it easier to remove the impregnated winding pack from the form. By separating the VPI process into two steps, dry spots or epoxy rich regions in the winding pack are avoided by minimizing the amount of material through which the epoxy must flow. The second step ensures that the aluminum crepe ground wrap is fully bonded to the winding pack, eliminating voids between the winding pack turns and the ground plane which could provide an arc path when the magnet is cooled to operating temperatures.

1.2.1.5 Coil Instrumentation

Coil instrumentation can be separated into two types -- quench detection and other (electrical, thermal, and structural) instrumentation. The quench detection system will consist of three fully independent systems -- internal co-wound voltage taps, internal fiber optic temperature sensors, and external flowmeters. These are being provided by the Project and will not be described here.

Adding strain gauges and temperature sensors to monitor the coil can, (and often does) add electrical fault modes or introduces stray voltages and noise that could interfere with the normal operation of the quench detection system. The fiber optic sensors would be available for routine or diagnostic temperature measurements, and there will be temperature sensors on the coil case from which the winding pack temperature could be inferred. For these reasons, adding instrumentation to the coils is not recommended.

The coil shield ground must be lifted in order to verify the integrity of the ground wrap. Each coil ground wrap is separated into two pieces, with a break in the middle of the coil and at the lead area. Single point grounding cables will be provided for each half, originating in the lead area. The actual location for the ground termination of these cables has not been specified by the Project, but the ground should be cold (4K), otherwise the high-conductivity grounding cables will conduct significant heat into the magnet system.

1.2.1.6 Coil Manufacturing Process

The coil manufacturing process is described in detail in Section 3.3. From a design standpoint, the winding pack tolerance is critical for two reasons. First, the winding pack must not have dry or epoxy-rich regions between layers and turns to avoid structurally weak areas that have insufficient shear strength and may crack under load. Misalignment of the coil turns may compress the insulation, preventing full impregnation, or unreinforced areas may exist, or stress concentrations may occur between turns. A misalignment tolerance of no more than 10% of the turn gap, or about 6 mils is recommended. Second, the coil must be accurately positioned within the case to mitigate the build up of field errors arising from deviations in coil shape and case manufacturing.

To zero order, the coil must fit within a case. In the transition region of the case, the worst case large coil and small case just contact. If this happens in several places, the case for that coil would have to be remachined, with significant additional expense and project delay. In addition, the TF magnet system is allocated only 8% of the $n=1,2$ field error terms. A 1-mm radial shift of one TF coil consumes 11.8% for the $n=1,2$ field error terms. As will be discussed in Section 1.2.2.6, the goal is coil placement to within ± 0.005 in, which gives about an order of magnitude improvement in field error. Shifts of the order of 1 mm are

possible, and can be cancelled by adjustments in the positions of adjacent coils without case remachining, if the coils do not consume the fabrication tolerance.

During coil winding the desired bend radius must be attained at each step. The coil will be wound into a form, with in-to-out layers being wound against the first turn and the form, while out-to-in turns being wound against the last turn and the form. At each bend step, the length of bent material and the angle subtended accurately measure, then the radius should be correct or can be corrected by clamping just the turn against previous turns. If the length of material bent is incorrect, then this simple adjustment can not be done, and a banana gap or a transition shift will occur. Adding high precision angular reference marks to the form, and accurately metering and marking the conduit material, it should be possible to control the winding pack build at the .006 inch level.

1.2.2 TF Structure

1.2.2.1 General

The TF octant with coils, leads, supports and cryo distribution elements is shown in Figure 1.2-11. Two octants are assembled into a quadrant, and four quadrants are brought together in the Test Cell at PPPL to form the TF magnet. A TF magnet cross-section view showing the general arrangement of the structure is shown in Figure 1.2-12.

The TF winding pack (Figure 1.2-2) is encased in a heavy stainless steel weldment which is the TF coil case. Inside the ground wrap, the coil electrical insulation is epoxy impregnated glass cloth. Outside the ground wrap, the coil-to-case potting is a glass-filled (low CTE) room temperature cure epoxy. This epoxy filler sets the position of the coil within the case with respect to fiducials on the octant structure.

An 0.4-inch nominal gap between coil and case provides clearance during assembly when the coil is mated with the case. All voids between the coil and the case will be filled -- structural calculations show that insulation stresses are increased significantly if the case compression is reduced (see Section 2.2.2). By using a filled epoxy whose CTE is matched to that of the case, the potting will not contract away from the case during cooldown. The tendency for voids to develop during final potting will be controlled by the vacuum/pressure filling process. It is not required that the potting adhere to the case surface, since there should be compression between the materials, and small gaps and cracks that may form during operation would have ground potential on both sides.

The TF coil cases are a steel-plate welded-up structures generally with full penetration welds. The details of the case subassemblies are shown in Figures 1.2-13 through 1.2-17. The main fabrication sequence is shown in Figures 1.2-18 through 1.2-29. The TF Magnet System is a full bolted structure. Figures 1.2-30 through 1.2-32 show the assembly of the bolted joints at final assembly. The structures that encase each TF coil are the primary structure for the total superconducting magnet system. All PF coils, FECC coils, the cold-mass support system attachments, and a number of lead and cryogen mounting brackets are made to the TF-coil-case primary structure, as shown in Fig. 1.2-11.

The in-plane Lorentz force loading seen by each TF coil is a non-uniform burst pressure with a resultant body force which is directed radially inboard toward the center of the tokamak. This inboard leg burst loading is reacted by wedging the 16 TF coil case inboard legs together. The cross-sections of the inboard legs are "keystone" shaped, and they fit together to form a closed circular section as shown in Figure 1.2-12. The wedging loads are reacted by hoop compression in the thick steel nose sections of the TF coil cases.

Figure 1.2-11 TF Octant Assembly

Figure 1.2-12 TF Magnet Assembly (Dwg. D-1332100)

Figure 1.2-13 Inboard Leg Assembly (Dwg. C-1334300)

Figure 1.2-16 Inter-Coil Structure Subassembly (Dwg. D-1334221)

Figure 1.2-17 Left Bolting Assembly (Dwg. D-1334100)

Figure 1.2-18 TF Octant Assembly Nomenclature

Figure 1.2-19 TF Octant Fabrication Sequence - Inboard Leg

Figure 1.2-20 TF Octant Fabrication Sequence - Add Coil Cases

Figure 1.2-21 TF Octant Fabrication Sequence - Add Inter-Coil Structures

Figure 1.2-22 Inter-Coil Structure Detail

Figure 1.2-23 TF Octant Fabrication Sequence - Add Outboard Details

Figure 1.2-24 TF Octant Fabrication Sequence - Add Winding Pack

Figure 1.2-25 TF Octant Fabrication Sequence - Add Side Assembly

Figure 1.2-26 Inboard Side Plate Weld Detail

Figure 1.2-27 Outboard Leg Weld Detail

Figure 1.2-28 TF Octant Fabrication Sequence - Add Lead Box

Figure 1.2-29 Lead Box Structure

Figure 1.2-30 TF Magnet Bolted Joint

Figure 1.2-31 Bolted Joint Assembly Detail

Figure 1.2-32 Bolted Joint Insulation Detail

Figure 1.2-33 Bolted Joint Wedge detail

Eddy current breaks are located at eight inboard leg wedging faces. The eddy current insulation consists of two 1.25 mm thick G-10 sheets, bonded to the opposing wedged octant faces with complete coverage. Structural calculations indicate that the top and the bottom of the inboard leg do not wedge as required under the combined loads of TF and PF coils. In final design, we will look at the addition of small rectangular shear keys, or higher friction surface insulation such as sprayed alumina, to react this load.

The TF outboard leg also experiences an in-plane burst pressure which is directed radially outboard. This loading is reacted by tying the outboard legs together with an inter-coil tension structure, which also reacts the out-of-plane loads experienced by the TF coils. The inter-coil structure is comprised of two steel plates 1.5 in thick, with 1-in ribs between the plates. Detailed structural calculations have been used to simplify the design by removing unnecessary ribs, and to relocate others to provide more support in critical regions. The plates are curved in the vertical direction and straight in the toroidal direction, so that the plate contour can be shaped by rolling. The eddy current break is located in the center joint of the four-coil module. Preloaded tension bolts and interlocking tapered shear keys, have been used to transmit loads through the joints.

Winding pack electrical insulation is also an important component in the TF magnet structural design. The insulation is a sandwich type structure with layers of Kapton and S2-glass cloth bonded together with epoxy. The Kapton is adjacent to the Incoloy 908 conduit, and forms a slip plane between the conduit and the glass-epoxy composite. The presence of a slip plane generally reduces tension and shear in the insulation, while increasing the stress in the conduits and allowing conduit motion. For the TF magnet system, this additional structural load on the conduits is not a problem.

There are two problems with the structural behavior of epoxy/glass laminated insulation that led to the new insulation baseline design described previously. The first is the poor tension strength of epoxy bonds perpendicular to the reinforcement layers. The second potential problem is poor interlaminar shear strength parallel to the insulation layers. The interlaminar shear strength of the insulation is significantly better if the interlaminar shear is accompanied by compression normal to the layers.

Both of the above problems are reduced in the TF magnet system when compared to the "caseless" PF magnets, by choosing a coil design approach that drives the coil insulation into compression on cool-down. The TF magnet uses the following:

- A low contraction steel conductor conduit material (Incoloy 908)
- A high contraction steel TF case material (316LN stainless steel)
- An epoxy/glass filler material with a low coefficient of thermal expansion.

The combination of material thicknesses and contraction coefficients used in the TPX design are reasonably matched. Therefore, the coil electrical insulation should be loaded in compression after cool-down to operating temperatures. However, it has been difficult to achieve compression of the winding pack insulation in the TF magnets throughout the cool-down period. The higher contraction rate of the winding pack and the contraction differential between the winding pack insulation and the conduits are the main drivers. The use of 3D S2 glass materials has reduced the shear to allowable levels, even in the presence of tension stress. Interlaminar allowable shear stresses are discussed further in the structure analysis of Section 2.2.2.

1.2.2.2 Structure Materials and Properties

The TF coil structure material is 316LN stainless steel in the annealed condition. The weld filler material is Inconel 625. The conduit material is Incoloy 908. The properties of these materials, as well as selection criteria, are presented in Materials and Process Selection, SDRL 21.

1.2.2.3 Structure Fabrication and Assembly

The TF structure fabrication sequence is shown in Figures 1.2-18 through 1.2-29, with many of the sub-assembly welds identified in Figures 1.2-13 -1.2-17. Additional process information for coil and case fabrication can be found in Section 3.3.

TF structure welding can be subdivided into two basic types -- subassembly welds and closure welds. Most of the welding will be done at the subassembly stage in a weld shop environment; however, some of the TF structure welding must be done under more controlled conditions, for example closure welding of a TF coil case with a cured coil inside the case. Most of the subassembly welds are full penetration, with the exception of some of the intercoil structure rib welds, such as those shown in Section C-C of Figure 1.2-15. The welding filler material is Inconel 625. Compared to stainless steel-filled weldments in 316LN, Inconel 625-filled weldments are stronger, have lower distortion, less tendency to crack, and will not form magnetic inclusions.

Significant effort has gone into limiting weld distortion during case fabrication, minimizing the required cleanup machining while producing a structure with very high precision for coil placement (± 0.005 inch is the target) and octant mating. In order to accomplish this, the following process plan will be followed:

- The inboard leg and intercoil structure weldments will be performed in a welding fixture
- The filler material is Inconel 625.
- Prior to final machining of the case cavity for coil installation, the structure (at the level of Figure 1.2-23) will be stress relieved by annealing
- Datum points will be placed at strategic and visible locations on the inboard leg and outboard case structure. These will be used to define the final case machining, coil placement, octant-octant final machining, and can also be used for final alignment of the TF magnet system in the test cell.
- The final case machining will be done in a fabrication fixture, with all cuts -- nose, octant case sides, and coil case channels, performed in a single set up. All octants will be final machined using the same fabrication fixture.
- After installation of the coil and the bolted joint side assemblies, the octant will be returned to the fabrication fixture for final machining.

The full octant case structure, with all major subassemblies identified, is shown in Figure 1.2-18. The case fabrication starts with the inboard leg subassembly. The nose region is one of the highest stress areas of the TF structure. Additionally, there are very tight tolerance requirements on nose fabrication, both for wedging and for field error tolerances. For that reason the central section of the nose, including the CS facing plate, is a single forging, as shown in Detail E of Figure 1.2-15.

Next the coil case rings are added to the inboard leg subassembly. The inner intercoil structure and LHe cooling line are added, followed by the outer intercoil structure. At this point (Figure 1.2-21) the case cooling channels in the inner case side wall are added, the case is stress relieved, fiducial references added, and the case is finish-machined.

The winding pack is added, partially potted to lock in alignment relative to the case fiducials, and the side bolting assemblies are added. The critical case closure welds are made, as shown in Figures 1.2-26 and 1.2-27 for the inboard and outboard structures respectively. Finally, the lead box is added, as shown in Figure 1.2-28, completing the octant. Some parts of the lead box are welded to the case, while other pieces are bolted in place, primarily to permit access to the box interior for maintenance and repair, as shown in Figure 1.2-29. Structural calculations indicate that the lead box area does not carry high stresses, so bolting is acceptable.

1.2.2.4 Structure Cooling

Figure 1.2-10 shows the coolant flow schematic for a TF octant. Each flow path supplies two layers of the coil. Flow enters at three points and exits at four points for each coil. Layers adjacent to the coil case receive higher heat loads from neutron and eddy current heating deposited in the case. Consequently, flow in these layers is from inside (higher field region) out to keep the higher temperature helium away from the high field regions. Each cooling feed circuit includes a filter, flowmeter and electrical isolator. Return circuits include an isolator and a flowmeter.

Two of the LHe returns from the coil are used to feed case cooling loops. The present heat load calculations indicate that case cooling is required. In the conceptual design, Mueller type panels were proposed for intercepting the heat from the inter-coil structure. These have been replaced by three case cooling loops -- two loops in the coil case sidewalls and one cooling the outboard intercoil structure. Placing a cooling loop on the ICS intercepts much of the nuclear heating that would otherwise go to the coils, while at the same time reducing the temperature differential between the coil case and the ICS and hence limiting thermally-induced distortion.

The splice blocks for the coil-to-coil joints and coil-to-bus joints are also cooled, with the circuits indicated in Figure 1.2-10.

1.2.2.5 Magnet Assembly and Alignment

The TF magnet design has component symmetry at the octant level and eight bolted interfaces with eddy current break insulation. This represents a significant departure from the conceptual design, which was a bolted/welded structure -- two octant modules are brought together at a bolted interface to form a quadrant, and quadrants are welded together at final assembly. The final weld buildup compensates for quadrant misalignments, while the weld contraction should provide outboard leg compression to wedge the structure when still warm.

However, such a method also has negative features. First, the bolted joint is the first assembly operation, and it must fit at the expense of the more critical inboard leg alignment. The octant structure is asymmetric -- the two octant sides (one bolted, one welded) are different structurally. The bolted joint is stiffer than the welded joint in bending, and this leads to significant differences in the ICS structural loads. Finally, the structural distortion due to welding cannot be corrected after the welding is completed.

During preliminary design, a number of new design drivers have affected the case configuration. First, detailed analysis showed that the welded joint thickness had to be increased to reduce the membrane stress to allowable levels, further increasing the structural asymmetry. Second, in ECP-038 a new diagnostic port was added, passing through the right hand side of the middle of the welded joint. About half the material in the center third

of the welded joint would have to be removed to accommodate the diagnostic port. With half the material removed, the other half of the center of the welded joint would have no structural value. The addition of the port begs for a full equatorial opening in the center of the welded joint.

Since the membrane stress is already near the allowable limit, the thickness of the ICS plates would have to be further increased in the balance of the welded joint to accommodate this change. Further, field error analysis indicated that the inboard leg alignment is more important than the outboard leg alignment, which provides an additional reason to try to improve the inboard leg alignment.

The field error allocated to the TF magnet in the "A Spec" is only 8% of the total $n=1$ and 2 field error components, while a single 1-mm shift of a TF coil radially outward constitutes 11.8% of the field error allowable. The impact of a toroidal rotation of a TF coil is less important, about half that of a radial shift, so we can permit higher rotational error in the outboard leg if it means that the radial alignment of the inboard leg is improved. Finally, the conceptual bolted joint placed the eddy current break insulators in high shear -- and the radial hoop shear competes with the toroidal overturning shear to produce insulation requirements that would be very challenging to meet if one cannot depend on friction in the joint to hold the surfaces together.

Many existing tokamaks report difficulty with the cyclic ratcheting of the eddy current break materials, and it is just this competition between shear and friction that is the origin of this type of problem. Winding pack insulation shear stress analyses show that the insulation behaves more favorably when placed in sufficient compression to overcome any developed tension loads during operation, and this is a desirable goal for the TPX eddy current break insulation as well.

With these factors in mind, a fully bolted configuration of octants was developed, with the following design goals:

- Allow the addition of the MSE diagnostic port
- Improve the inboard leg alignment control by allowing outboard leg misalignment
- Place the EC break insulation under compression to permit higher shear margin
- Provide a uniform toroidal pretension in the outboard bolted structures to pull the TF magnet system together
- Define an assembly sequence that permits enhanced alignment of octants for structural and field error drivers.

A fully bolted octant design has been developed which meets the above design goals. The main features of the design are shown in Figures 1.2-30 through 1.2-33. The TF magnet now consists of identical octants which are structurally symmetric; they are fabricated with a single tooling fixture, and can be assembled in any order to minimize the build up of field errors. The toroidal and radial shear are taken by the tapered keys, each of which has two studs pre-loaded to about 1 MN each to buck the operating loads. The stud nuts have build in tensioning elements, based on the "Superbolt" concept.

The bolts are electrically insulated from the flanges as part of the eddy current break insulation, which also includes glass/epoxy composite insulators between the wedge faces (Figure 1.2-32), placed under compression by the toroidal preload. The slotted flanges are premachined at the factory. Final adjustments for misalignments are made in machining the tapered wedges, with a tolerance goal for bolted flange machining of ± 0.005 in. Fixturing or compression structures are not required to bring the assembly together.

The final fit up in the test cell will determine the wedge dimensions. If final fit up and machining is accomplished at the factory with the mating part of the tokamak support structure, then additional match machining of the wedges at PPPL will not be required.

1.2.3 Inter-Coil Connections and Instrumentation

The 16 coils of the TF magnet are electrically connected in series, in two interleaves of 8 coils each. Hence there are a total of four coil-to-bus joints and 12 coil-to-coil joints. All interconnections will be made with splice joints similar to that described in Section 2.3.7.

Figure 1.2-34 shows the coil-to-bus splice joint, which accomodates the preliminary coil design with identical leads. The coil-to-bus splice shown is a "handshake" configuration, while the other (not shown), would be done in a "praying hands" configuration. In Figure 1.2-33, the lead portion hanging in space is the NbTi bus conductor. The lead box side wall, upper FECC (in blue), and the quadrant bolted joint are also visible in the figure. The conductors will be fully supported (not shown). The bus routing down the side of the TF structure remains the same, and other components such as the FECC are not affected by the coil-to-bus connection arrangement.

Quench detection instrumentation will be specified by the Project for assembly into the TF magnet system; no other instrumentation interfaces directly with the coils.

Other instrumentation requirements include the ability to lift the octant grounds to verify octant electrical isolation. The location of the cold single point ground has not been defined; a high electrical conductivity path will be provided from each octant to the cold ground, as well as an instrument cable for ac injection to verify the isolation the octant. The method of breaking the ground to verify isolation will be developed in final design.

Temperature sensors are needed on the structure in the nose region, mid-ICS, case walls near the ICS, and in the vicinity of the mounting structures for the support structure, CS, PF and FECC systems to verify structural cool-down and operating temperature distributions. Carbon resistors will be used, glued into mounting blocks soldered to the structure, and placed under any taping or MLI. These sensors are simple, robust, and sufficiently accurate for this application. Other types of temperature instrumentation could be used for compatibility with other sensors used on TPX.

Strain gauges will be installed on the TF structure to verify the structural load predictions and to aid in the initial checkout of the magnet system. Such gauges must be compensated for temperature and magnetic field, and they must be mounted such that the interface does not obscure the strain to be measured. Arrays of at least two gauges will be used, but as many as six in a group have been employed in superconducting magnets. There are a variety of off-the-shelf gauges, including multiple-gauge arrays, that can be used in this way, and the decision on which to adopt will again be based on compatibility with other TPX applications.

All strain gauges will be mounted on the exposed surfaces of TF coil cases and the intercoil structure, using compatible adhesives. Each of the eight octants will have six strain gauge sets, three located on the inboard leg nose, at the top center and bottom in such a way that they do not interfere with the eddy current breaks, and three will be mounted on the outboard legs next to the equatorial port. Of the outboard sets, two will be placed near opposite corners of the port to sense the coil case overturning stresses (the highest in the TF system), and the other will be located on the upper bolted joint flange to assess the global toroidal load.

Figure 1.2-34 Coil-to-Bus Splice Joint

1.3 TF Local Instrumentation and Control (WBS 135)

To be provided by LLNL

1.3.1 Sensor Interfaces

1.3.2 Data Acquisition Systems

1.3.3 Quench and Fault Detection

1.3.3.1 Normal Zone Voltage Detection

1.3.3.2 Cryogenic Cooling System

1.3.3.3 Gas-Cooled Leads

1.3.3.4 Monitoring Other Systems

1.3.4 Interlocks and Hardwired Interfaces

1.3.5 Interface to Central I&C

1.4 TF Bus and Leads (WBS 136)

To be provided by LLNL

1.4.1 Magnet Leads and Superconducting Bus

1.4.2 Bus Routing and Vacuum Barrier

1.4.3 Bus-to-Lead Interface

1.4.4 Gas-Cooled Lead

1.4.5 Instrumentation

2. DESIGN BASIS

2.1 Codes and Standards

The TF Magnet System design shall conform to the following standards that have been issued by the TPX project:

- TPX-STND-001, TPX Structural and Cryogenic Design Criteria
- TPX-STND-002, TPX Seismic Design Criteria
- TPX-STND-004, TPX Grounding for Personnel and Equipment Safety
- TPX-STND-005, TPX Material Properties Handbook.

In addition, the following codes or standards will be used to the extent applicable in the unique configuration and environment of a tokamak:

- Materials - American Society for Testing and Materials (ASTM) standards
- Welding and Brazing - American Welding Society (AWS) and American Society of Mechanical Engineers (ASME) standards
- Fasteners - Society of Automotive Engineers (SAE), ASTM and ASME standards
- Cleaning and Finishes - American Vacuum Society standards (as proposed)
- Electrical - Institute of Electrical and Electronic Engineers (IEEE) standards, National Electric Manufacturers Association (NEMA) standards and the National Electric Code (NEC).

2.2 Magnet Analysis

Details of the analyses performed to verify the TF magnet preliminary design are contained in SDRL 29. This section contains a summary of these activities and significant results.

2.2.1 Electromagnetic Analysis

3-D electromagnetic models were constructed in OPERA/TOSCA and AMPERES for the electromagnetic analysis for the TPX TF magnet. The models include not only the TF coils but also PF coils and plasma current at different operating states. The TF magnet at low operating temperature and the leads connecting the TF coils were also modeled. For better accuracy, all 84 turns of a TF coil were considered in some models for critical field analysis.

Confirmatory calculations were made of the toroidal field in the plasma region, the peak field, the field ripple, self inductance, mutual inductance, and the stored energy. The results are in good agreement with the Laboratory's calculations. The University-supplied plasma current has been used to calculate the electromagnetic loads on the TF coils for 3-D and 2-D models to support the structural analysis, and the magnetic field in the coil windings to support thermal analysis.

The sensitivity of the field error Fourier expansion to all possible degrees of freedom in coil displacement was determined for evaluating both TF and PF rigid coil misalignment effects. Various types of Monte-Carlo simulations were made to identify the most likely field error that a TF magnet would produce, and the major contributors to the worst field errors. The results of the simulations provided quantitative values for establishment of manufacturing tolerances in parts fabrication and coil positioning.

Table 2.2.1-1 shows part of the sensitivity analysis results for the effects of misalignment of a TF coil. Figure 2.2.1-1 shows the results of Monte-Carlo simulations of all 16 TF coils with 1 mm rms tolerance in six degrees of displacement freedom.

Table 2.2.1-1 Field Error Amplitude vs. TF Coil Displacements

Coil	disp	amount	c_{11}	c_{21}	c_{31}	c_{41}
TF1	dR	1/4"	1.497	0.171	0.311	0.092
TF1	d Φ	0.1°	0.088	0.005	0.014	0.007
TF1	dZ	1/4"	0.349	0.091	0.085	0.007
TF1	pitch	0.075° [†]	0.480	0.011	0.070	0.038
TF1	yaw	0.075° [†]	0.117	0.111	0.001	0.030
TF1	roll	0.119° [†]	0.875	0.000	0.189	0.032

[†] Angles correspond to tilts 1/8" at one edge of a TF coil, and -1/8" at the edge on the opposite side.

Figure 2.2.1-1 The Probability of c_{11} as a Function of c_{11}

The smooth curve shows the distribution, and the bars show the integrated probability within the ranges shown. The data were obtained from 10 million simulations. All six degrees of displacement freedom were considered and the rms tolerance of each is 1 mm translated to the edges of the coils.

2.2.2 TF Structural Analysis

2.2.2.1 TF Magnet Global Structure Analysis

Global structural calculations were performed in the preliminary design phase to provide a general evaluation of the structural integrity of the TPX TF Magnet System components. These calculations were performed using a finite element model that represented the TF structure. In addition to determining the integrity of the TF structure, the results of global modeling have been used for input to other activities such as magnetic field error calculations, to define loads for testing, and for definition of geometric envelopes and attachment displacements for critical interfaces.

The model was prepared to analyze the structural response of the system to loads which will be applied during manufacture, handling, installation, and operation. Loadings analyzed to date include cooldown to 4 deg. K and forces induced by magnetic field interaction. These loadings were used with variations of the finite element model geometry to evaluate several different design configurations investigated over the course of the preliminary design phase.

Some of the design options analyzed included:

- Opening the inter-coil structure at the equator in all 16 ICS segments;
- All-bolted assembly vs. four bolted joints and four welded joints;
- Reductions in the ICS reinforcement connecting the inner and outer shells
- Variations in the bolted joint configuration for improved insulator stability.

In the final design phase, more detailed analysis will be performed on the final configuration to address all the structural issues defined by the TPX Structural and Cryogenic Design Criteria. In these calculations, the effects of other loads will be considered, including halo disruptions, deadweight, handling and transportation, seismics, as well as thermal gradients induced by eddy currents, neutronic heating, and cool-down and warm-up

The results of the preliminary phase global structural evaluations have indicated that the TPX TF Structure is adequately designed to accommodate the expected operation. The peak stress intensities at the corners of the equatorial windows in the outboard leg structure (see Figure 2.2.2-1) increased by about 10% as a result of opening all 16 ICS segments. The stresses in the inboard leg have remained essentially unchanged from the conceptual calculations by the design changes. The stresses acting on the eddy current break insulation materials in the baseline design are acceptable, but it was noted that much of the insulation does not have sufficient compression to assure that the interface won't slip. Figure 2.2.2-2 shows areas of insufficient compression as white regions.

2.2.2.2 Coil Case Fracture Mechanics Analysis

The global structural model results indicate that the maximum principal stress in the TF structure is located in the coil case at the interior corner towards the tokamak centerline. This maximum principal stress is 265 MPa, and is located near a partial penetration seal weld, requiring a specification of the minimum penetration of the weld. Since the weld and base metals have different coefficients of thermal expansion at low temperatures, there will be a higher level of stress in the vicinity of the weld joints than if the joints were purely 316LN. This increased stress near the heat affected zone is estimated to be 155 MPa greater than that of the 316LN base metal, which brings the total alternating stress level in the region to approximately 420 MPa.

Figure 2.2.2-1 Stress Intensity in Inter-Coil Structure

Figure 2.2.2-2 Ratio of Shear to Normal Stress in Eddy Current Break

A Paris Law estimation of the fatigue crack growth rate was used to establish the minimum allowable weld penetration which would tolerate this level of stress for a fatigue life of 120,000 cycles. A partial penetration weld in the inboard leg region of the coil case with Inconel 625 filler metal will require 1.14 inch minimum penetration. These results are based on an estimate of the fatigue crack growth rate of Inconel 718, a similar material in lieu of the availability of Paris law data for Inconel 625 at 4K. S-N data for Inconel 600, on the other hand, indicate that the fatigue allowable stress could be higher for Inconel 625 at low temperatures.

The global model and sub-model calculated the maximum stress acting on a coil case weld away from the inboard leg to be 110 MPa, with the maximum located in the outer shell of the outboard leg near the equatorial port. Fracture mechanics analysis of this region found the maximum tolerable stress to be 280 MPa for the inner shell and 310 MPa for the outer shell.

2.2.2.3 CICC Fracture Mechanics Analysis:

A Paris Law estimation of the CICC stress was used to establish the maximum allowable flaw size in the coil conduit. The maximum stress in the (PF) CICC is approximately 446 MPa. The maximum allowable crack depth was estimated by a single-edge notch assumption, and was found to be 0.037 inch. This maximum flaw depth was then used as a parameter for establishing the maximum allowable crack length assuming the crack to be a semi-elliptical surface flaw. This maximum length is approximately 0.09 inch. At the minimum detectable depth, the maximum allowable crack length was found to be about 1 inch.

2.2.2.4 Winding Pack Analysis

A solid model of the TF winding pack was generated using I-Deas Master Series for design purposes to verify Laboratory drawings, optimize the winding pack configuration, section portions of the winding pack for 2D and 3D analysis, and ultimately, to generate part and assembly drawings.

The CICC winding path, which is used to generate the conduit solid model, has been used to generate precise points along the path for the 3D thermal-hydraulic model, magnetics and field error analysis, and also for use by manufacturing to program the winding machine. These data include the x,y,z coordinates of the start and stop point of each entity (line, arc, splice) which defines the path, as well as the entity length and cumulative length of the path. From the winding pack solid geometry, cross sections have been taken throughout the transition region to help understand this area as well as define the spacer geometry. With the transition region cross sections, 2D analysis was initiated to determine the stresses during cool-down.

The modeling process has allowed all 16 TF coils to be made identical to provide interchangeability and to reduce costs. The leads and He stubs of the TF coil have been optimized, in conjunction with the solid modeling of the leadbox components, to develop a coil design which is common for all locations in the TF magnet. With the modeling completed, part and assembly drawings have been generated directly from the solid geometry. Any changes to the TF CICC winding, leads, and He stubs can be automatically updated on the drawings.

The baseline insulation design has evolved from the need to alleviate structural problems apparent in the conceptual insulation design. The conceptual design is a US-DPC style

glass fiber reinforced composite, which included both glass fiber wrapped around the conduit and glass fiber barriers between conduit turns and layers. Two problems were addressed at the conceptual stage -- the poor tension strength of the epoxy bond perpendicular to the layers, and poor interlaminar shear strength.

The conceptual design addressed the tension problem by adopting the ITER criteria of no tension perpendicular to the laminates. A shear stress criterion was also adopted, based on the intrinsic shear strength of the epoxy in the composite plus an enhancement factor based on the normal compressive loads on the insulative material. The conceptual design used a high-contraction steel (316LN) around the winding pack. With a low contraction steel (Incoloy 908) as conduit material, and relatively small insulation thicknesses, this approach was considered adequate to keep the winding pack in compression during cool-down.

Subsequent detailed analyses of the winding pack has shown that the conceptual design did not achieve its goal of keeping the insulation in compression during cooldown. The analysis documented in SDRL 29 describes the complex winding pack stress distribution. The results in Table 2.2.2-1 indicate that the choice of glass composites and epoxy potting materials for installing the winding pack into the case are more important than the case itself.

Due to the high contraction of the conceptual baseline composites, a net tension can be seen in the winding pack (Figure 2.2.2-3). This behavior is observed in both the transition regions and at the equatorial regions. To resolve this problem, glass fiber reinforcement materials with a 3D weave have been identified that have near-isotropic properties and are a closer thermal contraction match to the incoloy conduits. These same characteristics are desired in the ground plane insulation. A low-contraction potting compound between the winding pack and the coil case is also important.

By introducing these materials, the stainless steel coil case is able to provide enough compression so that local tensions are small in comparison, and the insulation remains in compression. This compression is high enough that the insulation meets the shear stress criterion. An additional benefit of the selected material is a move away from traditional laminar composites to a design that is able to handle small through-thickness tensions, such as those introduced under magnetic loading.

*Table 2.2.2-1 Comparative Stresses in Composite Insulations
with 3D and 2D Fiberglass Weaves*

Stress Comparisons: Detailed Equatorial Model with 2D Ground Plane to Detailed Equatorial Model with 3D Ground Plane					
	Sx (In Plane)	Sy (Thru-thick)	Sxy	Sz	Sint
Equatorial Model with 3D GP					
Conduit	-701 144	-85 20	<1	81 320	760
Kapton Layer	-198 66	-150 20	10	-167 56	
3D Overwrap	-301 254	-150 23	80	-51 167	
Corner Fill	-212 160	-260 60	75	1 100	
Ground Plane	-265 68	-160 18	49		
Equatorial Model with 2D GP					
Conduit	-657 140	-66 25	<1	90 324	740
Kapton Layer	-170 70	-197 23	10	-140 56	
3D Overwrap	-300 214	-225 37	88	-30 187	
Corner Fill	-272 50	-113 144	86	-7 115	
Ground Plane	-279 63	-170 18	46		

* Stresses in MPa

RESULTS: 2- B.C. 1,LOAD 0,STRESS_2
STRESS - X MIN:-4.18E+04 MAX: 3.63E+04 psi
DEFORMATION: 1- B.C. 1,LOAD 0,DISPLACEMENT_1
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 5.35E-02 inches
FRAME OF REF: PART

Stress values in psi

2.2.3 Thermal-Hydraulic Analysis

Thermal analysis of the TF magnets has been carried out to evaluate the preliminary design and to verify its thermal performance. The analysis covers both the effects of quench in the coil, and study of the thermal efficiency of cooling arrangements during a regular operating regime, in the presence of neutronic, eddy current and radiation heat loads.

The quench analysis considered normal zones initiated by both short and long disturbances. Short normal zones result in the highest hot spot temperature and small resistive voltage, which makes them difficult to detect. A study of the quench detection sensitivity shows that protection within allowables (maximum conductor temperature of 150K) is possible if a proper detection level is chosen. For a 5 -cm initial disturbance, the threshold voltage should be less than 0.81 V.

A quench starting from a long disturbance develops a high pressure inside the conduit and a significant helium expulsion flow rate. These predictions are very sensitive to an accurate description of the magnetic field distribution and its correlation with the current sharing temperature. The maximum pressure during a quench caused by a 5-m disturbance can exceed 7-8 MPa, and the maximum expulsion mass flow rate is around 100g/s. The parameters of a quench with a 5-m initial disturbance length are summarized in Table 2.2.3-1.

Table 2.2.3-1 Long-Disturbance Quench Characteristics

Parameter	$p_{out}=0.3$ MPa $T_{in} = 5$ K $\dot{m}=4.7$ g/s	$p_{out}=0.3$ MPa $T_{in} = 6$ K $\dot{m}=4.7$ g/s	$p_{out}=0.25$ MPa $T_{in} = 6$ K $\dot{m}=3.91$ g/s
$T_{cable\ max}$ (K)	112	124	129
p_{max} (MPa)	7.9	8.9	7.5
Max. expulsion flow (g/s)	96	110	102
Zone length @ 10 s (m)	101.5	Full pancake	Full pancake

To evaluate the effectiveness of the cooling design, a detailed steady-state 3-D thermal-hydraulic model has been built. It consists of two submodels, coupled through iterative runs. The first submodel is a steady-state thermal hydraulic code (SSTH, written by B&W) for one-dimensional helium flow in the TF double pancakes with thermal coupling between turns. The second submodel is of the coil case and intercoil structure, represented by 12 sections along the circumference of the coil, and employs the finite volume code TEMPEST.

The joint model has demonstrated fast convergence and capabilities for detailed analysis of the temperature and heat flux distribution, both in the CICC and in the support structure. It allows accurate estimation of the amount of heat intercepted by the cooling channels, and the impact of channel parameters and location on the CICC stability margin. Cooling channels

in the intercoil structure efficiently intercept a significant portion of the heat load. The efficiency of the channels in the coil case increases if they are located closer to the winding pack corners, where they can intercept heat deposited both in the inner (outer) and side walls of the case.

2.2.4 Radiation Damage Analysis (to be provided by the Laboratory)

2.2.5 Failure Modes Effects and Criticality Analysis (FMECA)

A preliminary TF magnet FMECA has been performed (SDRL 21), with the objectives of developing a design and manufacturing processes that minimize the chance of failure, and to identify maintenance actions that may be required.

Failures in the TF coils and coil components are expected to be rare. Structure and insulation design criteria provide sufficient margin for safe, reliable operation over the TPX lifetime. However, due to the severity of effect, failures of the superconductor and winding pack insulation are among the most critical failure modes; the time estimated for replacement of a magnet coil or two-coil module is nearly one year. A cold performance test of each coil or octant before integration into the tokamak could mitigate the schedule and cost risk of a processing defect that would not otherwise be detected until the cold mass was fully assembled.

Depending on location, a helium leak would be a critical failure mode because low helium pressures, around 10^{-5} g/cc could allow Paschen breakdown that reduce insulation effectiveness and potentially lead to coil damage. This risk is mitigated by venting the lead box volume to the cryostat such that the pressure in the lead box will not reach the Paschen region for small leaks.

Many superconducting magnet problems are associated with the coil end terminations and instrumentation. Potential failures include leaks at fittings, insulators, connecting tubing, manifolds, headers and connectors; malfunction of instrumentation such as flowmeters, temperature transducers, and pressure transducers; and malfunction of valves and orifices for flow control. Because of uncertainty in component qualification status, a short across the helium line electrical isolator is identified as a critical failure mode. These risks are mitigated by ease of access to the lead box and internal components for repair. About two weeks are required for warm-up, repair within the lead box, and cool-down to operating conditions.

TF magnet misalignments causing excessive field errors and potential plasma disruption are identified as a critical failure mode. Such misalignments could be caused by initial assembly errors, by non-uniformities that produce non-symmetric structural deformations during cool-down or operation, or by material creep or slippage in magnet joints. The risk is mitigated by the ease of realigning the magnet bolted joints after magnetic field mapping, and by the possibility of installing additional field error corrector coils.

Failure modes in the TF Local I&C and Bus and Leads will be defined by LLNL. Redundant sensors and processing circuits are provided for quench detection, and quench protection circuits are installed to be fail safe.

2.3 R&D Summary

2.3.1 Quench Detection R&D - to be provided by the Laboratory

2.3.2 Conductor R&D - to be provided by the Laboratory

2.3.3 Coil Forming R&D

Coil forming research during Phase I covered three areas: (1) hydraulically assisted hand bending for lead and transition forming, (2) roll-forming of major coil radii, and (3) the effects of the reaction process on the stresses and dimensions of coils formed by the two previous methods. All three portions of this effort were intended to quantify the bending characteristics of CICC proposed for use on the TPX program.

Incoloy and stainless steel materials were tested, as were PF and TF CICC cross-sections. Empty conduit as well as copper filled dummy conductor were tested, although no prototypical TF dummy conductor was available. Measurements included dimensional changes induced by bending, the amount of material spring-back experienced, the effect of adding cold-work on conductor bending, weld seam orientation effects, the effect of different material and geometry on all of the above, and the effects (if any) of subjecting the various bend samples to the reaction process.

The purpose of the first effort was to study lead bending. A hand operated hydraulic bending tool was used to bend conduit to 6", 7.5", and 9" radii. Empty and copper-filled dummy conductors representative of all magnet types were tested (no TF dummy was available). TF conductor was bent in the "easy way" and "hard way". Bending empty conduit led to buckling at 6" radius regardless of the means of load application, although identical conductor filled with copper could be bent to 6" without significant dimensional degradation. Empty conduit could be formed to 9" radius without buckling, but significant dimensional degradation was experienced at 7.5" radius.

Spring-back values ranged from 10% to 15%. TF "hard-way" bends showed the least springback, as would be expected due to a greater amount of inelastic bending. Results for spring-back were very repeatable for a given piece of conductor, but were greatly affected by the type of metal being bent and the initial amount of cold-work present in the conductor.

A three-roll pyramid style bender was used for the roll-forming study. Empty and dummy conductors representative of all magnet types were tested (except no TF dummy was available). The effects of cold-work and dimensional changes were measured. All major magnet bend radii were simulated, as was "easy way" vs. "hard way" bending of empty TF conductor. When roll-formed to its minimum design radius of 40", TF conductor showed significant cross section distortion, indicating the need for side support of the conductor during bending. This feature has been incorporated in the design of the production roll-forming machine.

Cold-work has a significant impact on the as-formed radii resulting from a given roll setting. Results showed a change in as-formed radius of as much as 10" from a single bend and straighten operation, pointing up the importance of consistent conductor material properties. Small changes in relative roll location and rigidity were also demonstrated to have significant impact on the as-formed radii, indicating the need for the production roll-forming machine to have very rigid rolls and excellent position stability and repeatability.

The third phase of the study assessed the impact the reaction process on the as-formed dimensions of the various conductors. The reaction process does not significantly relax

restrained conductor; once a conductor is bent, it will spring back to the same position regardless of whether it was subjected to the reaction process in the restrained condition or not. Reacted Incoloy conductor shrinks approximately 0.1% indicating that reaction tooling must provide compliance, and that the as-formed coil must be slightly oversize to allow for the reaction-induced shrinkage. Unrestrained conductor did relieve an average of approximately 1°, indicating some slight relaxation. The most significant finding was that as-formed conductor kept its shape after reaction within the capability of our inspection equipment, indicating that reaction will not degrade as-formed dimensions.

2.3.4 Conductor Reaction and Sheath Cleaning R&D

The principal purposes of conductor reaction R&D in Phase I of the magnet program were to assess the temperature response of a CICC coil matrix to typical temperature-time profiles for superconductor reaction, and to develop methods to ensure uniform heating of the cross section. A finite element computer model of heat transfer within a TF coil cross section was developed and correlated with experimental results from coil matrix mockups to adjust for variations in the thermal emissivity, spacer conductivity, and for the effect of a partial chamber pressure in augmenting heat transfer. The computer model and analytical results are provided in SDRL 29, and the experimental setup and data are documented in SDRL 37.

The results indicate that high-conductivity, tabbed spacers between coil turns are effective in providing rapid and uniform response of the winding pack. The model predicts that the time lag between the chamber wall temperature and coil equilibrium is a small portion of the hold time at reaction temperature. The computer model can be used to evaluate chamber configuration and control variables (heater zone locations and power profiles) for a specific coil (or set of coils) and reaction temperature-time profile.

During the winding of the TPX coils, spacers are inserted in the turn-to-turn gap which ultimately will be occupied by insulation. This spacer maintains the dimensional accuracy of the coil during the thermal reaction cycle, and provides a thermal conduction path to the coil interior. Because of the extended thermal exposure, the effects of vacuum, and the mechanical pressures between turns, there is a risk of diffusion bonding between the spacer and the conduit. Diffusion bonding of the spacer would interfere with removal of the spacer and, if severe, could compromise the functionality of the conduit.

Diffusion bond testing of several candidate spacer materials was conducted, and the bonding risk for those materials in the bare metal state was identified. A boron nitride diffusion barrier was also tested, and consistently proved satisfactory in preventing bonding between the spacer and the conduit surface.

Alternative insulation designs to the TPX baseline call for a high strength bond between the vacuum impregnation resin and the surface of the conduit. This would permit the coil assembly to respond to thermal or mechanical loads monolithically, potentially reducing the stress in the conductor. Testing was conducted to evaluate the shear strength of the bond between the vacuum impregnation resin and the conduit surface after several alternate cleaning operations. The testing has identified reasonable cleaning techniques based on mechanical abrasion which result in a high strength bond at both room temperature and at cryogenic temperature.

2.3.5 Coil Insulation R&D

The TF magnet design and manufacturing processes are based on data from the coil insulation R&D conducted by Westinghouse during Phase I of the magnet development effort. Tests were conducted on 3 x 3 conductor matrixes to evaluate six alternative insulation configurations under mechanical and electrical stress. The selected baseline is a double-wrap of Kapton, free to slip on the conductor, backed by fiberglass tape impregnated with epoxy. The fiberglass tape and reinforcement at the conductor corners are woven with a 3-dimensional distribution of fibers, creating a more isotropic composite and lower stresses than conventional 2-dimensional weaves.

After baseline selection, 5 x 5 matrixes with TF and PF conductor were fabricated and tested to validate the design. Test data are provided in the PF PDR package.

2.3.6 Helium Stub Welding R&D

The TF magnet design and manufacturing processes incorporate the helium stub design developed by Westinghouse during Phase I of the development effort. A roto-bore tool is used to pierce the conduit wall. An oversized stub sleeve is welded to the conduit around the hole with an intermittent welding process to limit heating of the superconductor. After verification of full weld penetration within the sleeve, a second stub transition is attached with full weld penetration at the outer end of the sleeve.

Figure 2.3.6-1 is a diagram of the recommended configuration. Process development data are provided in the PF PDR package.

Figure 2.3.6-1 WEC Helium Stub Design

2.3.7 Coil Interconnection Component R&D

A conductor splice for coil interconnection has been developed by LLNL in Phase I of the magnet effort. The splice design is shown in Figure 2.3.7-1. This design will be fabricated and tested for verification of power loss and current capacity under simulated operating conditions in the MIT Pulsed Test Facility. Test data will be available at a later date.

Figure 2.3.7-1 LLNL Splice Design

3. DESIGN IMPLEMENTATION

The overall schedule of activities for final design, manufacture, and test of the TF magnet is contained in the Integrated TF Magnet Plan (SDRL 36). This section of the SDD contains descriptions of the activities required to proceed from preliminary design to magnet delivery at PPPL.

3.1 TF Magnet Final Design (WBS 133)

3.1.1 Specifications

A TF Magnet System Requirements Document has been prepared (SDRL 17); as have critical item specifications for the magnet coil and manufacturing equipment (SDRL 20). The flow down of requirements to these specifications was shown in the Forward to this document. Following completion and release of the Tokamak System Requirements Document ("A" spec) by PPPL, establishing traceability of derived and allocated requirements, the magnet specifications will be updated for release by PDR. A normal specification maintenance effort will extend through the final design phase.

Specifications for the magnet and bus conductors, and for the TF Local I&C and the TF Bus and Leads will be prepared by LLNL.

3.1.2 Interface Definition

Ten primary Interface Control Documents have been drafted during the preliminary design phase, identifying TF magnet interfaces with other TPX systems. These documents are listed below, and are provided in the PDR package as SDRL 18.

<i>TF Magnet System Interface with:</i>	<i>Document No.</i>
Vacuum Vessel (WBS 12)	TPX-ICDP-1213-0001
PF Magnet System (WBS 14)	TPX-ICDP-1314-0001
Cryostat (WBS 15)	TPX-ICDP-1315-0001
Tokamak Support Structure (WBS 16)	TPX-ICDP-1316-0001
Tokamak Assembly (WBS 17)	TPX-ICDP-1317-0001
Field Error Correction Coils (WBS 19)	TPX-ICDP-1319-0001
Vacuum Pump Ducts (WBS 34)	TPX-ICDP-1334-0001
Electrical Power System (WBS 42)	TPX-ICDP-1342-0001
Instr. & Control System (WBS 61)	TPX-ICDP-1361-0001
Cryogenic Equipment (WBS 72)	TPX-ICDP-1372-0001

These ICDs are at an early stage of definition, and considerable effort will be needed during the final design phase to coordinate quantitative interface requirements and document interface details on drawings. In addition, the following three secondary ICDs are to be prepared by LLNL, defining interfaces between segments of the TF magnet system:

TF Magnet/TF Bus & Leads	TPX-ICDS-133-136-01
TF Magnet/TF Local I&C	TPX-ICDS-133-135-01
TF Bus & Leads/TF Local I&C	TPX-ICDS-135-136-01

3.1.3 *Materials and Processes Selection*

A preliminary data base of materials, components, and processes used in fabrication of the TF magnet has been prepared, and is provided in the PDR package as SDRL 21. Materials and processes used in the TF Local I&C and in the TF Bus and Leads will be added to the data base, which will be maintained throughout the final design phase. This data base will be coordinated with the Project, assuring uniform application of material properties and qualification criteria across the TPX systems.

While many selected materials have well-documented properties in the TPX operational environment, some components and processes are not well characterized and will require further testing. These items are identified below in Section 3.3.3.1, Material and Component Testing, and in Section 3.3.1, Manufacturing Process Development.

3.1.4 *Electromagnetic Analysis*

In final design, it will be necessary to accomplish the following electromagnetic analysis tasks:

- Add the joggles, leads and bus conductors to the TOSCA models.
- Determine or provide information for the determination of the new one-turn compensation requirements of the PF system for final lead and joggle geometries of the TF magnet system.
- Extend the TF field error analysis to the PF and FECC magnet systems in order to integrate field error mitigation.
- Assess the impact of Incoloy 908 on the fields in the vacuum vessel during transient conditions and to aid in developing a field mapping technique.
- Develop a method of computing the fields of conduits clad with Incoloy 908 that is compatible with the plasma equilibrium codes so that the Incoloy impact can be corrected in the plasma modeling.
- Follow Incoloy 908 corrected plasma modeling with revised operating fields for various TPX scenarios.
- Determine the effects of halo currents and other operating anomalies.
- Perform electric field calculations of the winding pack and lead geometries to assess the worst case electrical stress for design adjustment.
- Perform an electric field sensitivity analysis on the effects of voids.

3.1.5 *Winding Pack Design and Analysis*

For the final winding pack design:

- The results of the preliminary design analyses must be folded back into the winding pack designs.
- Assuming success for the insulation R&D effort, measurements of actual structural and thermal properties will have to be made during final design in order to assure that the design analyses match the actual winding pack characteristics.
- The presence of voids in the winding pack composites has been ignored in the preliminary design. Since defects cannot be avoided, and the winding pack is very sensitive to fine structural details, a sensitivity analysis must be done to establish premissible void density levels. The sensitivity of stress to misalignment of the conductor turns must also be assessed.

- Conduit springback after bending is a factor of material hardness and the level of cold work prior to bending. A predictor/corrector system, based on information obtained from processes like spool payout and straightening, must be developed.
- The insulation stress testing in preliminary design has not successfully resolved the differences between compression-induced tension and tension-induced tension, and bi-directional loading tests are recommended in final design to resolve this issue.

3.1.6 Structure Design and Analysis

In the structural design area, the following tasks must be accomplished in final design:

- Further assess and resolve bolted joint constructability issues.
- Develop a model for welding distortion of 316LN.
- Accommodate the FECC mounting and heat loads.
- Define the interface with the support structure.
- Define the TF MLI system.
- Continue integration of PF operating loads, mounts and coil alignment with the TF system.
- Assess the effects of halo disruptions and other operating anomalies.
- Continue assembly and constructability assessments of the complete TF magnet system.
- Define support and lifting requirements for final assembly, including supporting the vacuum vessel. Assess handling and transportation loads, and design necessary handling points and fixture interfaces.
- Define and implement the interface to the cold system electrical ground.

3.1.7 Thermal Design and Analysis

Quench Performance

- Model a fast quench during DT reaction, with zone initiation caused by neutronic heating (no external disturbance). Strong nuclear heating will continue during the quench, which raises the helium temperature everywhere in a layer in a few seconds. Possibly multiple zones will exist, and definitely pressures and mass flow rates will be higher. If the results are too bad (very high $\dot{m}$ and p_{max}), we may need to verify the analysis by another code (such as CICC at LLNL), since the modified QUENCHER code can handle only substantially subsonic flow.
- Determine quench sensitivity to the friction factor and heat transfer coefficient in the conduit.
- Perform refined analyses as more detailed characteristics of CICC become available from the conductor supplier.

Transient Analysis (lower priority)

- Convert QUENCHER to a transient thermal-hydraulic code.
- Define transient regimes and loads, rough estimate of heat coming from the structure.
- Analyze DD and DT transient characteristics.

Stability Analysis (lower priority)

- Determine stability margin.
- Build or modify a numerical code to calculate stability margin for a uniform disturbance applied to one strand, or to many strands.
- Determine transient heat transfer to helium, and current redistribution between strands. Check with the code CICC by R. Wong at LLNL.

Thermal-Hydraulic Steady-State Performance

- Refine calculations
- Further optimize case cooling channel positions, trade-off between manufacturability and performance
- Determine more accurate heat loads (neutronic + eddy + radiation)
- Determine sensitivities to:
 - friction factor
 - inlet temperature and flow rate
 - uncertainty in value and distribution of heat loads

3.1.8 Instrumentation and Control

In this area, the following work is needed:

- Better define the Local I&C system to select instrumentation components, including allowed signal types and levels, available DA and AD channels, bit resolution and data rates.
- Define the technique for lifting ground to verify electrical isolation of components, including the AC injection requirements.
- Develop cold testing methods to verify the mounting, as well as the temperature and field compensation of the chosen strain gages

3.1.9 Magnet Interconnections

The TF case cooling design (in which case cooling follows the coils) must be reconciled with Project plans to provide higher temperature, lower pressure helium returning from the buses. The TF coil temperature margin is very sensitive to the case cooling feed temperature.

3.2 TF Conductor Acquisition (WBS 132)

To be provided by the Laboratory

- 3.2.1 Strand Qualification and Production
- 3.2.2 Cabling Qualification and Production
- 3.2.3 Conduit Qualification and Production

3.3 TF Magnet Fabrication and Test (WBS 133)

3.3.1 Manufacturing Process Development

During Phase I of the magnet development program, basic R&D was conducted in the areas of coil forming, reaction, and insulation; the installation of helium stubs; and conductor joint evaluation. The status of manufacturing R&D is summarized in section 2.3. Coil bending and reaction R&D was performed by B&W, and further information is contained in SDRL 37.

During Phase II, the basic R&D will be extended to support development of manufacturing equipment and tooling, and to qualify the equipment and processes for production of the TF magnet. Preliminary designs of equipment and tooling are described in SDRL 22, and the equipment specifications are in SDRL 20.

3.3.1.1 Coil Winding Process Development

In support of a final winding machine design that meets the stringent coil forming accuracy requirement, analysis of the sensitivity of bend radius to variability in both the machine and conductor will be continued. Since dummy TF conductor was not available in Phase I, early fabrication of small lots of dummy conductor is recommended. Empirical data from TF bending trials are needed to ensure control of cross section deformation and precise measurement of the developed length in bends.

During development of the winding equipment, additional dummy conductor will be used for machine checkout and acceptance. Final acceptance of the machine and tooling will be predicated on forming at least two layers of the TF coil in conformance with the specification, requiring approximately 200 m of continuous dummy conductor for each trial.

3.3.1.2 Coil Reaction Process Development

Using empirical data from Phase I R&D, thermal models of the reaction chamber and various coil configurations will be analyzed to develop specific configurations of heater banks and baffles needed to meet the coil reaction temperature accuracy requirement. The dummy coil fabricated during acceptance of the winding machine will be instrumented to verify the temperature profile in the winding pack for reaction furnace acceptance.

When the conductor supplier(s) is selected, criteria for internal contamination of the conductor must be developed that allow a reasonable period for evacuation and purging to an oxygen concentration consistent with SAGBO control. Sample testing will be required to rationalize the cable and sheath fabrication processes with the need for low levels of contamination.

3.3.1.3 Coil Insulation Process Development

The baseline insulation configuration developed in Phase I consists of a double wrap of Kapton and a single over-wrap of 3D-weave S2 fiberglass tape on the conductor; 3D-weave corner reinforcement; and a multi-layer coil ground wrap with an intermediate conductive electro-static shield. This matrix is impregnated with epoxy in a two-stage vacuum pressure impregnation process. Further sample testing required to qualify the design and process is discussed in section 3.3.3.1.

A mockup of several layers of a full-scale TF coil will be fabricated to develop the method and tooling for release of the conductor from the reaction fixture, wrapping, and placement

with corner roving in the VPI mold. Additional mockups will be fabricated to assess mold seals around the helium stubs and leads.

3.3.1.4 Structure Fabrication and Coil Assembly

The TF structure consists of eight identical two-coil modules, each a weldment of heavy sections of 316LN stainless steel, and containing helium cooling tubes. The inter-coil structure is stress-relieved and machined to precise dimensions after welding. After installation of the coils, the case covers are welded in place and the entire module is machined to final dimensions.

Mockups of the structural weld joints will be processed to develop weld parameters and qualify the operators. Analytical models will be used to predict the distortion of the case when subjected to different welding sequences. A quarter-scale mockup of an entire two-coil module will be fabricated to verify the weld distortion predictions.

A mockup of the cooling channel in the nose forging will be fabricated to develop the process for installation of the cooling tube, to verify thermal compatibility during cool-down, and to assess inspection methods.

The finished TF coil is potted in place in the coil case, using a fiberglass-filled epoxy. A mockup will be fabricated to develop the potting process and tooling, particularly the seal between the coil case and the helium stubs and leads in the lead box. The mockup will be used to evaluate the epoxy's flow characteristics and its ability to fill the cavity without voids; and its compatibility with the coil and case during cool-down. The mockup will also be used to develop the insulation juncture between the potted coil and the manually-applied wrap in the lead box.

3.3.1.5 Component Process Development

Superconducting Splice Joint Development - Basic R&D on a splice joint was conducted by LLNL during Phase I; and R&D on instrumentation lead extraction and sealing has been performed by MIT. The design of the splice joint between the TF coils will require modification to accommodate misalignment of the coil leads without bending the leads. Mockups of the splice joint will be fabricated to develop methods and tooling for process steps that include;

- Conduit stripping from reacted superconductor
- Acid and rinse baths to remove the chrome coating from the strands in both vertical and horizontal attitudes
- Superconductor soldering to the splice block
- Conduit and helium line welded or brazed connections
- Instrument lead splices and sealing techniques.

Joints fabricated by the selected methods will be sent to the MIT Pulsed Test Facility for performance verification.

Helium Stub Welds - A conduit piercing method and basic weld joint design were developed during Phase I to meet criteria of full weld penetration without damaging the superconductor. Additional mockups will be fabricated to simplify the baseline joint, to determine process control limits and conductor cooling methods, and to train operators. The mockups will be tested at cryogenic temperatures to verify crack-free performance.

Magnet Interconnections - A mockup of the lead box will be fabricated to characterize and verify the design, assembly procedures, and inspection methods for magnet interconnection. The mockup will ensure that clearance exists for tooling to make the conductor splices and helium line joints, and that access is adequate for insulation application. The mockup will be used to train construction trades for installation operations at PPPL.

3.3.2 Preliminary Magnet Manufacturing Plan

A complete Manufacturing Plan (SDRL 38) will be developed in Phase II; preliminary data are contained in the following Phase I SDRL items:

	<i>TF Coil Fabrication - (Wind, React, Insulate)</i>	<i>Structure Fabrication and Magnet Assembly</i>
Process definition, equipment drawings, supporting analyses, and procurement plans	SDRL 22	SDRL 32
Equipment specifications	SDRL 20	N/A
Manufacturing R&D data	SDRL 37	N/A
Process times, staffing, mfg. controls, and facility layout	SDRL 3	SDRL 3
Verification (Test & QC)	SDRL 33	SDRL 45
Long Lead Items	SDRL 25	SDRL 25
Schedule and Cost data	SDRL 36	SDRL 36

The referenced SDRL items are as follows:

- 3 Management Plan
- 20 Critical Item Specifications
- 22 Critical Equipment Drawings, Specifications, and Procurement Plans
- 25 Long Lead Materials and Equipment
- 32 Coil Assembly Documentation
- 33 Coil Verification Testing Plan
- 36 Integrated Magnet Plan
- 37 Manufacturing R&D Plans and Results
- 45 Acceptance Test Plans

This section contains summary descriptions of the equipment and process steps for coil winding, reaction, insulation, and magnet assembly. Figure 3.3.2-1 provides an overview of the manufacturing sequence, with required parts and tooling identified at each step.

Figure 3.3.2-1 TF Magnet Manufacturing Sequence

3.3.2.1 Coil Winding

The required dimensional accuracy of the TF coil is driven by three requirements:

1. The coils must fit within the high strength structural case.
2. The magnetic field perturbations due to geometric variations in the coil must be within a stringent tolerance.
3. The variation in spacing between turns must be consistent with the compressibility of the insulation material in order to ensure reliability under high operating stress.

The first two requirements are met primarily by forming the coils to an accurately machined tool that provides the required shape. As each turn is formed, it is separated from the preceding turn by metal spacers, and the matrix is clamped to the tool. The bending radius specified for each turn is slightly biased to compress the spacers between the turns.

Winding machine accuracy is driven largely by the third requirement: insulation reliability. The insulation system contains a woven fiberglass tape impregnated with an epoxy. If the spacing between turns is too small, the fiberglass reinforcement will be over-compressed and epoxy impregnation may be incomplete, leaving voids; if the spacing is too large, the epoxy may not be adequately reinforced ("resin-rich") and will crack. Misalignment of the conductor turns will also cause stress concentrations, potentially overstressing and fracturing the insulation. The objective for variation in turn-to-turn spacing is $\pm 10\%$ of the nominal spacing of 0.064 inch, or ± 0.006 inch.

Factors affecting the accuracy of coil forming include:

- Variations in the conductor yield strength and cross section, causing variable springback or twist;
- Deformation of the conductor cross section (crushing or keystoneing);
- Errors in the measurement of conductor length to the current bend point, due to sensor error, slippage, conductor elongation, etc.;
- Errors in forming the local radius due to roller eccentricity, machine compliance, control error, etc.

The conductor will be clamped to the coil form tool, compensating for long-period errors in bend radius. Short-period variations in bend radius (comparable in length to the clamp spacing), twist or keystoneing of the conductor cross section, and errors in developed length will be difficult to correct manually, and would require an excessive amount of hand work during the forming process.

The Coil Winding Equipment, shown in Figure 3.3.2-2, includes the following major elements:

- a. Despooler - Holds a reel of conductor for payout to the straightener. The despooler has two axes of motion: rotational for payout, and along the spool axis to maintain a constant conductor position entering the straightener. The despooler will be powered to provide resistance to the conductor drive, and to function as a takeup when the system is operated in reverse.

Figure 3.3.2-2 Coil Winding Equipment Diagram

- b. Straightener - Straightens the conductor as it feeds off the spool when forming a coil. Straightening provides a uniform strain and level of cold work in the conduit entering the roll bender. The straightener will be capable of being operated in reverse as a roll bender to form the conductor for respooling, if required by fault conditions during coil fabrication.

- c. Roll Bender - Forms the required radius of curvature in the conductor at every position along the conductor length. The roll bender will be located in a fixed position with respect to the straightener, and over the tangent to the winding table. Conductor leaving the roll bender spirals down to the coil form on the winding table. The roll bender includes sensors to continuously measure the length of conductor from the start of the coil to the current bend point, and the as-formed radius. The roll bender also includes capabilities to prevent deformation of the conductor cross section, and to correct for conductor twist during bending.
- d. Winding Table - Supports the coil form tool and moves the coil form in three axes (x , y , θ) to maintain the coil position corresponding to the current bend point directly under the fixed roll bender. By appropriate control of the center of rotation of the table, and with an appropriate coil form tool, the TF winding equipment can be configured to wind any of the TPX PF coils.
- e. Control System - Integrates data defining the required coil shape with real-time machine measurements and operator commands to control the forming operation. The control system also records data providing a log of all pertinent coil forming parameters for later quality verification and problem diagnosis.

The coil winding process includes the following steps, shown in flow chart form in Figure 3.3.2-3:

- a. A spool of conductor is installed on the despooler, and the appropriate coil form tool is mounted on the winding table. Sufficient conductor is separated from the spool and bent to calibrate the relationship between roll bender parameters and the radius of curvature achieved. Bending calibration data and the coil form data set are loaded, and the equipment is checked out.
- b. A reusable lead is attached to the conductor to thread the straightener. The straightener is jogged sufficiently to thread the roll bender. It is then further jogged to provide the coil lead, which is bent in the plane of the coil and attached to the coil form tool guides.
- c. Layer forming is initiated on the perimeter of the coil containing the leads. As the first layer is formed, the conductor is shaped and seated on the coil form, and restraining clamps are used to secure the conductor to the coil form. A spacer strip is installed manually between succeeding turns. Turn-to-turn transitions to permit nesting of the turns in the plane of the layer are defined in the coil form data set.
- d. The turns of the first coil layer are formed in the above manner until approximately 30° before completion of the final turn. The manually-operated bending tool is installed on the conductor, and the layer-to-layer transition bend is executed. The spacer strip is bent simultaneously with the conductor.
- e. Layer-to-layer spacer plates shaped to fit the contour of the coil are installed to separate the first and second layers.
- f. The turns of the second layer are now formed in the opposite sequence to the first layer.
- g. As defined by the design drawings, the conduit is pierced in alternate transition bends, and a tubular stub for coolant flow is welded to the outer surface.

Figure 3.3.2-3 Coil Winding Process

- h. After completion of the last layer, the manual bending tool is used to form the lead bends. The completed coil is removed from the winding table in its coil form tool; or it is banded and removed from the tool, which remains on the winding table.

3.3.2.2 Coil Reaction

After a coil is wound, the Nb_3Sn is reacted at elevated temperature for approximately 20 days to diffuse Sn into Nb, forming a superconducting intermetallic. The reaction process must be performed with a specific temperature-time profile at all points on the coil to achieve optimum superconductor properties. Since the Incoloy 908 conduit is susceptible to cracking in the presence of oxygen at elevated temperature, stringent control of the atmosphere within and surrounding the conduit is essential.

The TF coil reaction chamber is sized for two TF coils, or a combination of TF and PF coils as a production contingency. The equipment includes the following major elements, as shown in Figure 3.3.2-4:

Figure 3.3.2-4 TF Coil Reaction Equipment

- a. Vacuum/Partial Pressure Furnace. The furnace will be a front loading box furnace equipped with a door that pivots or slides for access to the interior of the chamber. The furnace walls will be insulated to minimize heat loss, and water cooled to provide a safe external temperature and to expedite cool-down at the end of the reaction cycle. The furnace floor will support the charge loading system and a work platform.
- b. Vacuum System. The furnace will be equipped with two parallel vacuum systems which normally work together to establish and maintain the furnace vacuum. When the furnace is operated with a partial pressure of inert gas, one of the vacuum systems will be valved off and the other throttled to reduce gas consumption. Either vacuum system will be capable of maintaining the specified vacuum in the furnace should the other system fail.

The system will be equipped with a Residual Gas Analyzer (RGA) on the chamber vacuum manifold, with sensitivity optimized for species with Atomic Mass Units less than 100. A leak checking capability using a helium leak detector or RGA with audible signal will be provided for the chamber and the gaps between all dual seals. Provisions will be made for continuous contamination monitoring at the inert gas inlets to the chamber and the charge, and at the charge purge outlet.

- c. Partial Pressurization System. The equipment includes a chamber feed-through, regulator, valves, a gas scrubber, and plumbing to an inert gas supply, capable of maintaining an inert gas atmosphere in the furnace at a pressure less than one atm.
- d. Charge Purge System. The equipment includes chamber feed-throughs, an internal distribution manifold, a gas scrubber, valves, a regulator, and plumbing to an inert gas supply, capable of flowing inert gas to the charge and collecting the purge gas and exhausting it outside the chamber.
- e. Heater System. The equipment includes power supplies, distribution cables and chamber feed-throughs, and radiant heater banks arranged in independent zones; the number and locations of zones will be determined for each charge configuration, based on the temperature uniformity and reliability requirements. Feed-throughs and external cabling to the control system will also be provided for up to 36 thermocouples attached to the charge.
- f. Chamber Wall Cooling System. The equipment includes a closed-loop water circulation system which maintains the furnace walls above room temperature to prevent condensation when the furnace is idle, and near room temperature for safety when the furnace is in operation. The system will include necessary water conditioning equipment and a cooling tower located outdoors and protected against freezing.
- g. Internal Cooling System. The equipment includes air-cooled panels within the chamber to expedite charge cool-down by radiant heat transfer. The cooling circuit will contain necessary blowers and ducts to an outdoor exhaust, and will have provisions for evacuation, isolation, and filling with helium for leak checking before the introduction of air.
- h. Charge Loading System. The equipment includes a transfer cart for loading the charge, and guide rails extending outside the furnace. The transfer cart interfaces with fixtures that support the charge. If the transfer cart is removed during reaction, stands will be provided to support the charge and jacking devices to transfer the charge

between the cart and the stand. The rails outside the furnace will be movable to provide clearance for closure of the furnace door and to permit storage when not in use.

- i. **Control and Data Logging Systems.** The equipment includes a computer or programmable controller, peripheral devices, interconnections, and software capable of automated execution of the reaction cycle and recording data that provide a log of process parameters. The system will control the power applied to each heater zone in response to charge temperature variations from a stored program. The system will also actuate valves and pumping systems to maintain the chamber vacuum or atmosphere in accordance with a stored program. The system will monitor and record temperatures from the charge mounted thermocouples, and the furnace vacuum level or partial pressure level. The system will contain self diagnostics, logic to avoid catastrophic temperature regimes, and sufficient redundancy to tolerate electronic part faults. The system will be equipped with a manual override for process changes and fault response by the operator.
- j. **Backup Power System.** The equipment will contain a backup power system capable of continuously operating all systems except the heating and cooling systems in the event of a facility power disruption. As an option, a backup diesel generator can be provided to operate all functions in the event of a prolonged utility outage.

The reaction process consists of the following steps, shown in flow chart form in Figure 3.3.2-5:

- a. The furnace charge will be determined by coil production considerations. A thermal model of the charge will be analyzed before the charge is assembled to determine a configuration of heaters and baffles that will ensure temperature uniformity. Necessary fixture modifications will be fabricated, and the reaction process control program will be established based on the type of superconductor and results of the thermal analysis.
- b. The coil(s) is transferred by crane from the winding station to the reaction equipment transfer cart. Thermocouples, internal heater banks, and the conductor purge manifold and exhaust are installed. The charge is loaded into the furnace, and connections are made to the power, signal, and purge gas feed-throughs.
- c. Helium is flowed through the conductor to purge it of contaminants. The furnace is evacuated and the system is checked for leaks. Heat may be applied to accelerate outgassing of the conductor, until the oxygen concentration in both the purge exhaust and the chamber is less than 0.1 ppm.
- d. When the required oxygen concentration is reached, the reaction cycle is begun. Various types of superconductor require different reaction temperature-time profiles. The chamber may be backfilled with a partial pressure of argon to accelerate heating by convective heat transfer up to a temperature of 350°C.
- e. Above 350°C, vacuum is re-established and the cycle continued. A typical reaction cycle lasts 20 days.

Figure 3.3.2-5 Reaction Process

- f. When the reaction cycle is completed, power is removed from the heaters and the charge begins to cool by radiant heat transfer to the chamber walls. After helium leak checking, room temperature air will be introduced to the internal cooling panels and exhausted to the outdoors. A partial pressure of argon may be re-established in the chamber to accelerate cooldown.
- g. After cool-down, the chamber is opened and the charge is removed and inspected prior to release for further processing.

3.3.2.3 Coil Insulation

TF coils will be insulated with a two-stage Vacuum Pressure Impregnation (VPI) process:

- a. The conductor is released one turn at a time from the reaction fixture, and is wrapped with Kapton and fiberglass tape as it spirals into a VPI mold, as shown in Figure 3.3.2-6. The mold contains an inner fiberglass ground wrap layer.
- b. The wrapped coil is impregnated with epoxy (first stage) in its VPI mold.
- c. The cured coil is removed from the mold and wrapped with a conductive layer and insulating overwrap. Spacers are removed from the mold, allowing for the thickness of the outer wraps, and a second VPI stage is performed.

Figure 3.3.2-6 Conductor Wrapping Process

Figure 3.3.2-7 shows the coil cross section at the first and second VPI stages.

Figure 3.3.2-7 Coil Insulation at VPI Stages

The equipment used to perform the VPI process contains the following components, as shown in Figure 3.3.2-8:

- a. Vacuum- and pressure-tight, heated VPI molds that contain the coils during epoxy impregnation and pressure-curing. The VPI molds are portable, and are supported by stands that allow connection of manifolds on the underside of the molds. A vacuum system will be provided for evacuation of any mold. The molds will be covered with thermal insulation blankets for temperature uniformity, efficiency, and personnel safety.
- b. A vacuum- and pressure-tight chamber and motorized agitator for de-gassing and mixing the components of the epoxy used to impregnate the coils. The chamber will be elevated for drainage, and heated to control the viscosity of the compound. A vacuum system is provided for evacuation of the chamber.
- c. Heated piping and manifolds that feed the epoxy components to the mixing chamber and the mixed epoxy to the coil mold. Tubing will also be provided from a facility dry nitrogen supply to the mixing chamber and coil mold.
- d. A control and data logging system that initiates process operations from a single point, controls the mixing and curing temperatures, and that the records and displays data from the process.
- e. Cables and wiring that connect the various system elements and that connect to facility power.

Figure 3.3.2-8 VPI Equipment

The VPI process is comprised of the following steps, shown in the flow chart of Figure 3.3.2-9:

- a. The coil and mold are moved to the VPI station stand, and seals are installed around the coil leads and stubs. The mold cover will be installed, and epoxy manifold connections will be made. Electrical connections will be made to the mold for heater power and instrumentation. Vacuum and dry nitrogen pressure connections are made.
- b. Vacuum and pressure leak tightness of the mold and the empty epoxy mixing container are checked. Proper functioning of the control system is verified. Thermal insulation blankets are placed around the mold.
- c. The valve at the inlet of the epoxy supply pipe, and the pressurization valves are closed.
- d. The VPI mold is evacuated; the vacuum level is monitored, and pumping continued until a stable vacuum level is reached. Heat will be applied to the mold to accelerate out-gassing and to bring the coil to the proper temperature for impregnation.
- e. The epoxy mixing container is evacuated, and epoxy resin is introduced from the supply at ambient air pressure. Agitation is begun, and the evolution of bubbles and the vacuum level are monitored until a stable vacuum level is reached. Heat will be applied to reduce the viscosity of the epoxy resin.
- f. The accelerator or catalyst is metered into the epoxy mixing container, and the compound is mixed. When mixing and de-gassing are complete, the mixing container vacuum valve is closed and the container is pressurized with facility dry nitrogen.
- g. The valve at the inlet to the epoxy supply pipe is opened, and epoxy is allowed to flow under pressure into the evacuated VPI mold from the bottom. The appearance of epoxy at a uniform level in the overflow columns indicates that the mold is filled, at which point the supply pipe and vacuum manifold valves are closed.
- h. Pressure is applied to the liquid epoxy from the facility dry nitrogen supply, and the temperature of the mold is raised to the proper curing temperature. Pressure will normally be applied for approximately one hour. The curing cycle will take 40 to 60 hours at ambient pressure with intermediate temperature changes, depending on the epoxy type.
- i. After filling of the VPI mold, epoxy remaining in the mixing container is dumped, the feed pipe is removed, and the container and feed pipe are cleaned for re-use.
- j. Following coil impregnation and curing, power is removed from heaters and the VPI mold and coil cool to shop ambient temperature.
- k. The insulation blankets are removed, and the mold is dis-assembled for removal of the processed coil. The inlet manifolds and overflow columns contain hardened epoxy, and will be sawed off for removal from the mold. Portions of the mold surrounding the coil leads and stubs will be separated at their seals.
- l. Either at the VPI station, or at a separate station, the coil will be manually cleaned-up by removal of hardened epoxy remaining outside the end-product envelope, removal of seals, and smoothing of mold marks.

Figure 3.3.2-9 VPI Process

3.3.2.4 Octant Assembly

The TF magnet is composed of eight identical two-coil modules, each a weldment of 316LN structural parts. The inter-coil structure includes cases for the two coils. Placement of the coils to high accuracy relative to alignment references is essential to magnetic field quality in the tokamak. After the coils are installed, case covers are welded to the inter-coil structure, and the cavity between the coils and the case is filled with fiberglass-filled epoxy. The following is a summary of the structure fabrication and assembly process, which is fully described in SDRL 32:

- a. The intercoil structure is welded from 316LN stainless steel parts, including a T-section nose forging, the coil cases, and inter-coil box structures. Incoloy 625 is used as the weld filler for its low distortion characteristics and toughness. The finished inter-coil assembly is heat treated for stress relief to minimize later distortion. The outer edges of each coil case, to which the case cover assemblies will be welded, are machined to planes precisely located at $\pm 11.25^\circ$ with respect to tooling holes that define the octant vertical midplane.
- b. The completed coils, after VPI of the conductive shield and outer ground wrap, are set up in a measurement fixture. An eddy current probe and laser measurement system are used to accurately map the locations of the outer conductor surfaces through the insulation at a minimum of eight sections around the coil circumference. Data from the coil mapping are processed to determine the optimum location of the coil in the torus to minimize field errors.
- c. Each coil is placed in its case in a horizontal attitude, facing up, as shown in Figure 3.3.2-10. G-10 pads are custom-machined and bonded to the coil case to accurately locate the coil in the required position relative to the octant midplane fiducials. When the coil location is verified to be within ± 0.005 in. of the required position, the case is partly filled with epoxy to lock the coil in position.
- d. The first case cover is placed over the partially potted coil as shown in Figure 3.3.2-11, and welded in position. A vacuum/pressure closure tool is placed in the case gap and sealed around the leads and helium stubs. The structure is rotated so that the coil is in a vertical plane, and the case cavity is evacuated and backfilled with epoxy.
- e. Steps b. through d. are repeated for the second coil. After the coils are installed, the assembled octant is finish machined so that the inter-octant planes are $\pm 22.5^\circ$ from the vertical midplane.

Figure 3.3.2-10 Coil Installation in Inter-coil Structure

Figure 3.3.2-11 Case Cover Installation

3.3.2.5 Coil Lead Termination and Lead Box Completion

The splice joint connecting the two coils in an octant will be completed at the factory, and the lead box chimney will be installed. Inter-octant and bus connections will be made, and hydraulic lines and instrumentation will be installed during tokamak assembly at PPPL. Because the coil positions will be determined by magnetic field quality requirements, the relative locations of the leads will vary and the splice joints must accommodate this variation without lead bending after reaction. The following summary of the lead splicing operation is expanded in SDRL 32.

- a. Lead supports will be installed after the coils are potted into the coil cases. The position of the splice joint and the dimensions of the inter-lead splice block will be determined from measurements made in place. Marks will be made on the conductors defining the conduit ends, and the outer portions of conduit will be cut and stripped from the superconducting cable. The outer portion of cable will be cut back, exposing the instrumentation leads.
- b. The superconducting strands will be stripped of chrome coating by immersion in an acid bath. During this process, the instrumentation leads must be protected and a positive pressure maintained within the conductor to prevent acid wicking into the cable outside the splice area. After chrome removal, the area will be thoroughly rinsed.
- c. An adapter fitting will be welded or brazed to the conduit on each side of the splice. If necessary, a helium stub will be installed at the end each conductor.
- d. The inter-lead splice block will be positioned between the exposed cables, the cables will be clamped to the block, and the joint filled with solder.
- e. The helium volume around the joint will be closed by welding or brazing a sleeve between the conduit adapters on each end of the joint.
- f. The instrumentation leads extending from the cables will be spliced to corresponding leads in a pigtail leading to an interface connector as shown in Figure 3.3.2-12. After insulating the splices, a sleeve will be welded over the splices and the volume will be filled with epoxy to seal the lead exits.
- g. The lead box rear and sides will be welded to the case structure, as shown in Figure 3.3.2-13. The leads penetrating the side plates are wrapped with Kapton and a G-10 fitting maintains the dielectric separation of the leads and structure. The front and top of the lead box are bolted in place to complete the assembly, providing access for later installation of the helium lines and for maintenance.

Helium line assemblies, including isolators, filters, and flow meters will be provided as kits for installation at PPPL. Mechanical connections at the ends of the assemblies are planned, simplifying installation and maintenance. Splices between octants and at the four bus joints are also made at PPPL, with procedures similar to those described above.

Figure 3.3.2-12 Inter-Coil Splice Joint

Figure 3.3.2-13 Lead Box Installation

3.3.3 TF Magnet Test and Inspection

3.3.3.1 Material and Component Testing

Material and component tests for the TF magnet (SDRL 34) will provide information to validate component selection, design analyses, manufacturing processes, and test methods. All materials selected for use in the TF magnet are well characterized, and no material tests are planned. Process qualification tests follow process development, in which basic process parameters are established, tooling verified, and operators trained with mockup fabrication.

- a. Conduit evaluation. No TF conduit samples fabricated by production processes were available for assessment during Phase I. Before fabricating full-size coils, bend tests should be performed on samples to determine dimensional changes resulting from short-radius lead and transition bends. Material properties, dimensional, and color changes resulting from the reaction process will be evaluated, and inspection methods will be assessed.
- b. Coil insulation. A few samples of the baseline TF coil insulation design and VPI process were tested under uniaxial stress during Phase I. Further testing is required to qualify the design and processes under biaxial life-cycle loading, and on a larger number of samples. Phase II testing will also evaluate criteria for electrical acceptance, and will qualify the process with respect to criteria for resin-rich volumes and voids. The designs and processes for ground wrap and conductive layer application, and for potting the coils into the case will be evaluated. It is assumed that data will be available from ITER or other sources to verify the ability of the TPX insulation to withstand the TPX radiation environment.
- c. Lead box voltage isolation. Mockups will be fabricated and tested to verify the design and processes for insulating lead box components in place. Electrical testing will assess breakdown voltages from conduit-to-conduit, conduit-to-chimney wall, and conduit-to-case under a range of simulated operating environments.
- d. Splice joint qualification. Basic R&D on a splice concept and instrument lead extraction has been conducted at LLNL and MIT during Phase I. The R&D splice design may require modification to accommodate lead misalignment, and no evaluation of the combined splice and extracted-lead configuration has yet been performed. Mockups of the final design will be fabricated using LLNL-supplied conductor (including instrument leads), and tested at the MIT Pulsed Test Facility for conformance to criteria including splice resistance, leak tightness, and instrument lead splice integrity under simulated life-cycle thermal and magnetic conditions.
- e. Weld qualification. In accordance with the TPX Structural and Cryogenic Design Criteria, §I-4.1.1, weld joints will be evaluated for tensile strength, fatigue strength, and crack susceptibility. Samples will be tested to qualify welders and weld processes, until the variation in results from a minimum of six samples is less than $\pm 15\%$ of the mean. Welds to be qualified include the helium stub welds on Incoloy 908 conduit, and structural case welds in 316LN using Inconel 625 filler.
- f. Helium stub installation. In addition to weld qualification, helium stubs will be installed in multiple conductor samples to simplify and qualify the method for piercing the conduit, the design of the stub and weld, and the method for cooling the conductor to prevent heat damage. Non-destructive evaluation of the weld by eddy current or ultrasonic methods will also be assessed and calibrated.

- g. Hydraulic testing. Instrumentation and methods for leak checking and flow impedance testing will be evaluated using LLNL-supplied conductor.
- h. Eddy current breaks. Various techniques for accomplishing the voltage break between octants will be assessed for resistance to abrasion, cold shock, and cyclic load.
- i. Superconductor reaction. Witness samples of strand extracted from both ends of the conductor will be reacted concurrently with each coil. The samples will be tested for conformance to the critical current requirement by LLNL or the strand manufacturer. If possible, data should also be obtained to determine the sensitivity of conductor performance to strain of the conduit as well as the strand.
- j. Instrument and isolator qualification. Instruments such as flow meters and pressure gauges, and the helium line isolators will be selected and specified by LLNL. The Laboratory or the component vendor will be responsible for qualification to the applicable operating range and TPX environment.

3.3.3.2 Prototype Test

Individual coils used in both superconducting tokamaks built to date (T-15 in Russia and Tore Supra in France) were tested prior to installation in the assembly to ensure that defects were detected at the earliest practical stage of manufacture. Testing of the TPX TF prototype coil will verify manufacturing processes, but since a single coil cannot simulate the magnetic field and stresses in a complete torus, the test will not qualify the design of the superconducting coils or cable-in-conduit conductor. The facility and methods used in the prototype test may be applied to manufacturing process verification of each coil, and the test thus represents an essential part of quality assurance for the TPX project.

The objectives of the prototype coil test are to:

- Verify fabrication and assembly processes of the coil and case
- Verify manufacture of the conductor
- Verify coil diagnostics and instrumentation
- Obtain parameters for cryogenics verification (cool down time, temperature distribution, pressure drop, etc.)
- Verify leak tightness of the prototype coil and components
- Obtain quench characteristics and performance of the quench detection system
- Verify adequacy of the electrical insulation
- Measure joint resistance
- Assess performance in pulsed fields (optional)

Facility requirements for prototype coil testing are:

- Cryogenic system providing supercritical He mass flow of 25 g/s at 5-8 atm and 5 K at the coil inlet, and 5 g/s of LHe for power leads.
- Vapor cooled power leads, capable of 50 kA at 15 kV terminal-to-terminal
- Power supply capable of 50 kA DC at 12 V (48 V is preferred)
- Dump resistor, 50 kA, 15 kV terminal-to-terminal, 30 MJ.
- Vacuum chamber with LN2 shield - overall dimensions of the coil with the case are about 5.5 x 3.1 x 2 m.
- Vacuum system.
- Data acquisition system with at least 50 channels.
- Pulsed coils (optional), fed by an additional power supply
- Power distribution buses, breakers, etc. for 50 kA, 15 kV operation.

- LHe and LN2 distribution system
- He recovery system

The test article is the first TF Magnet Coil wound, heat treated, insulated and accepted in accordance with TPX-SPEC-133-0001. The coil will be installed in the octant casing, the cover will be welded, and potting completed. Additional fixtures will be fabricated to support the octant case in the chamber and to reinforce the nose region, replacing the effect of wedging between adjacent octants. Although this coil will possibly be more heavily instrumented than regular TF coils, the capability to use the prototype as a spare coil, if needed, will be retained.

The sequence of test operations is as follows:

- a. Cool down. This test will assess the characteristics of the coil cool down process, including verification of allowable parameters for mass flow, inlet-outlet temperature drop, efficiency of the cooling, and the effect of the reverse flow heat exchange between the pancakes.
- b. Charge coil up to full current. The coil will be charged to full (and possibly higher) current to determine the coil's current carrying capacity. Joint resistance and heat generation inside the coil will be measured. Acoustic emission signals and strain gauges will give information about mechanical integrity of the coil and whether the impregnated coil will have a tendency to separate from the casing.
- c. Verify performance of the normal zone detection system. A normal zone will be initiated with a built in heater and the response of all sensors (voltage taps, optical fibers, mass flow meters) will be checked to see whether their performance is as expected.
- d. Discharge at up to 2 kV terminal-to-terminal voltage, and high potential test up to 7.5 kV coil-to-ground. This test will verify that the insulation system will withstand the design voltage, and will verify the numerical simulation of a quench event (with a somewhat different scenario and stored energy than that in the real toroidal array). The response of normal zone detection system will give information on the system performance and sensitivity. A time delay may allow an adequate amount of heat to be deposited in the coil to simulate the coil performance in the real machine.
- e. Charge the coil at elevated temperature. This test will allow a study of the critical surface of the superconductor, by reaching the critical current at elevated temperatures. This information will show if the superconductor was degraded in comparison with its short sample test, and will verify the heat treatment process.
- f. Pulsed field (optional). Pulsed coils would be installed around the casing of the coil to generate a longitudinal and/or perpendicular magnetic field. This test would require additional non-superconducting copper coils and a pulsed power supply. Providing that pulsed field information will be available from straight samples, and depending on the stability margin measured in those tests, pulsed field tests may or may not be conducted on the prototype coil.

The overall duration of the prototype tests is estimated to be eight weeks, including the following activities:

- Assembly of coil inside the cryostat, make all connections - 2 weeks
- Cooldown -1 week

- Test time - 2 weeks.
- Warm up - 3 days
- Disassembly - 2 weeks.

Facility preparation should start at least 12 months prior to the test, assuming a basic facility like FENIX is available, allowing time for engineering and planning, development of preliminary and final designs, facility modification, and fabrication of fixtures.

The following actions are required to complete test planning:

- Make detailed cost and schedule estimates on all options, and make a decision to what option is the preferred.
- Obtain commitment for use of FENIX facility and support equipment
- Analyze cool down and complete preliminary cryogenic design
- Analyze coil forces at different currents and complete a preliminary fixture design
- Make a detailed list of parameters to be measured and verify adequacy of the existing data acquisition system
- Prepare a preliminary test plan and obtain approval from the TPX project.

3.3.3.3 TF Coil Verification

TF coil verification, described in SDRL 33, demonstrates conformance to the inspection and test requirements of TPX-SPEC-133-0001. The inspection and test sequence shown in Figure 3.3.3-1 starts with receipt of conductor and concludes with release of the formed, reacted, and insulated coil for assembly into a coil case. The activity symbols on this and later flow charts have the following meaning:

All coil verification tests (except for tests on reacted superconducting strand and leak tests after cold shock) are performed at room temperature. The coil ends and helium stubs are capped with tooling to enable pressure and leak testing after helium stub installation. The requirements to be verified in each test and the test equipment are detailed in Figure 3.3.3-2.

Figure 3.3.3-1 Coil Verification Flow

Verification Test	Derived From	Test Loc.	Rational for performing test	Phase of Production	Specification Requirement & Source / Test Requirement	Equipment Required	Equipment Sensitivity Required
1. Coil Insulation Integrity	TFMCS §3.2.1.1 §3.2.2.3	B&W	• Turn to Turn Insulation Integrity • Coil to Ground Insulation Integrity	• During Winding • Post-Insulation • Post VPI	• Turn - Turn = 10V inductive voltage during fast dump - test to 2700 volts impulse / induced (2x coil + 1) (per WBS 42- Power Supplies and Quench Protection) • max. Layer to layer = 240V inductive during fast dump • Coil to Ground > 7.5kV - Quench Voltage - Test to 2x+1=16kV dc Hipot (per WBS 42- Power Supplies and Quench Protection) • Ground wrap to case (with ground point lifted) 1kV dc	• dc High Potential Meter • Tan-Delta Meter • Induced Voltage System • Impulse test system • Shell for in process monitoring	• dc Hipot ⇒ 16kV production test ⇒ 0.01mA current trip • Impulse ⇒ 2.7kV • Induced Voltage ⇒ 2.7kV @ TBD Hz • Tan δ ⇒ 11.3kV AC ⇒ 60Hz
2. Coil Electrical Characteristics	TFMCS §3.2.1.1	B&W	• Basic electrical properties of coil	• Throughout Manufacturing	• Inductance = 50.7 mH for single coil • Resistance = 0.173 Ω per coil	• Test Cell system (power supply, volt meter, inductance meter)	• Power Supply ⇒ 10 amp x 2 V • LCR meter ⇒ 50.7 mH • Volt meter ⇒ 0.1mV accuracy
3. Pressure Testing	TFMCS §3.2.1.2	B&W	• Verify CICC Pressure Rating	• After Reaction	• CICC - 370 psig w/ TBD leakage.	• Pressurized Gas source • Pressure Transducers	• TBD
4. Helium Leak Testing	TFMCS §3.2.1.2	B&W	• Weld Integrity	• Throughout Manufacturing	• Pressurized conduit w/ TBD leakage	• Sonic Leak detection system	⇒ Background Null ⇒ 1x10 ⁻¹⁰⁰ l/s
5. Flow Impedance	TFMCS §3.2.1.3	B&W	• Verify pressure drop through winding does not exceed limit. • Verify pancake variability does not exceed limit	• Pre/Post Winding / Helium stub Installation	• operation SC He @ 5 ATM inlet - 2-3 ATM outlet • 26 g/s in TF coil SC He (7g/s through each winding) • Gas Argon Test (11 ATM drop @ 1.71 SCFM per Kelly Dixon)	• Flow meters • Pressure transducers • Pressurized Argon supply	• Flow meter ⇒ 2 SCFM, .01 res • Pressure Transducer ⇒ .05 psi
6. Instrumentation	TFMCS §3.2.1.4	B&W	• Verify that installed instrumentation is functioning.	• Throughout Manufacturing	• Fiber signal distance = TBD • Co-wound voltage tap Ohms = TBD • Co-wound voltage tap inductance	• Volt Meter • Current Supplies • Inductance meter • Fiber Optic Meter • TDR meter • Outside Lab	• TBD
7. Nb ₃ Sn Conductor Characteristics	TFMCS §3.3.1.5	Outside Lab	• Verify Critical Current • Reaction Cycle Verification	• Post-Reacting	• Witness strands reacted with coil. • I _c =		• N/A
8. Dimensional Inspection	TFMCS §3.2.2.1	B&W	• As built / reacted key dimensions	• Throughout Manufacturing	• Per Drawings	• Miscellaneous Dimensional Measurement Equipment	• TBD
9. Weld Inspection	TFMCS §3.3.1.2	B&W	• Ensure high quality welds	• Post Helium Stub Attachment • Post Splice Block Attachment	• TBD	• Die Penetration • Temperature Sticks • Ultra-Sonics	• TBD
10. CICC Crack Detection	TFMCS § TBD	B&W	• Cracks less than maximum allowable size	• Post-Reacting	• Maximum allowable crack size = • Long Crack - Depth not to exceed 10% wall thickness • Short Crack - under 55 mills long, depth not to exceed 20% of wall thickness	• Eddy Current Analysis system	• TBD
11. Conductor Splice	TBD	B&W	• Ensure solid bond between splice block and conductor	• Post Splice Block Attachment	• TBD	• Ultra Sonics • Test Cell equipment	• TBD

Figure 3.3.3-2 Coil Verification Requirements

3.3.3.4 TF Magnet Acceptance

TF magnet acceptance test and inspection, described in SDRL 45, spans from coil assembly into the case structure, through delivery to PPPL, and final cold tests of the assembled magnet systems in the TPX cryostat. The flow shown in Figure 3.3.3-3 assumes final machining and delivery of two-coil octants. Inter-coil splices within the octant are made at the factory, and the outboard leads are protected by tooling for delivery. Helium line and inter-octant connections are made in the field.

The process for dimensional inspection and placement of the coils in the octant cases to satisfy the allocated field error requirement is described in SDRL 32. Pre-assembly of the complete bolted structure at B&W is recommended if time allows. Alignment of the octant assemblies to simultaneously minimize field errors and optimize load distribution will require custom machining of the inter-octant wedges, and perhaps machining of the octant interfaces. These operations can be accomplished most efficiently at the factory, and the recommended final alignment can be recorded by fiducial marks for re-establishment at PPPL.

The tests performed during octant assembly are shown in Figure 3.3.3-4; these tests parallel the room temperature tests performed at the coil level, and verify that succeeding assembly operations have not damaged the coil. Electrical tests also verify the integrity of the coil ground wrap and outer conductive layer with respect to the case, lead box connections and insulation, and inter-octant resistive breaks.

Time permitting in the project schedule, a cold test of each octant is recommended enroute to PPPL. The TF Magnet Failure Modes Effects and Criticality Analysis has identified a number of potential defects that could prevent the magnet from reaching its required current and magnetic field, but that cannot be detected until the magnet is cold tested. The earliest cold test planned at present occurs after assembly of the complete cold mass and cryostat in the TPX test cell, approximately one year after TF magnet delivery. From the PPPL integration plan, we estimate that the time required to disassemble the cryostat and cold mass, replace a defective coil, and rebuild the system to return to the same point on the integration schedule, would be more than one year -- assuming that a spare coil were available. During this period of delay, work on later stages of tokamak integration would essentially be stopped.

Octant-level tests could use the same facility established for TF prototype testing. The test objective would be limited to verification of the coils' ability to achieve the required operating current. Since the magnetic field and stress in the octant configuration will be less than that in operation, the helium temperature would be increased to an equivalent test point on the critical surface.

Final assembly and test activities are shown in Figure 3.3.3-5. System tests of the assembled cold mass are the first opportunity to verify all performance requirements of the integrated TF Magnet System, including TF Local I&C, TF Bus and Leads, and the effects of interactions between the TF and PF coils and other TPX systems. Following performance verification, the magnetic field is mapped to determine the location of plasma facing components.

Figure 3.3.3-3 TF Magnet Factory Assembly and Acceptance

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Figure 3.3.3-4 TF Magnet Acceptance Requirements

Acceptance Test	Derived From	Test Loc.	Rational for performing test	Phase of Production	Specification Requirement & Source / Test Requirement	Equipment Required	Equipment Sensitivity Required
1. Dimensional Inspection	TFMSRD §3.1.2.10	B & W and TPX Site	• As built key dimensions	• Throughout manufacturing • After Delivery to TPX Site	• Per Drawings	• Misc.	• TBD
2. Coil Electrical Characteristics	TFMSRD §3.1.3.2	B & W and TPX Site	• Basic electrical properties of coil	• Throughout manufacturing • After Delivery to TPX Site	• Inductance = 50.7 mH for single coil • Resistance = 0.173 Ω per coil	• Test Cart system (power supply, volt meter, inductance meter)	• Power Supply $\Rightarrow$ 10 amp x 2 V • LCR meter $\Rightarrow$ 50.7 mH • Volt meter $\Rightarrow$ 0.1mV accuracy
3. Instrumentation	TFMSRD §3.2.1.3.	B & W and TPX Site	• Verify that installed instrumentation is functioning. • Verify instrumentation is electrically isolated from High Voltage components	• After installation • Upon Delivery to TPX Site • System level	• Co-wound voltage taps - Resistance = TBD • Direct wired voltage taps • Insulation from case = 18 kV • Flow Sensors • Strain Gages • Fiber Optics • Temperature Sensors	• Volt Meter • Current Supplies • Fiber Optic Meter	• TBD
4. Coil Insulation Integrity	TFMSRD §3.2.1.4	B & W and TPX Site	• Turn to Turn Insulation Integrity • Coil to Ground Insulation Integrity	• After installation in TF case • After Delivery to TPX Site	• Turn - Turn = 10V inductive voltage during fast dump - test to 2000 volts Impulse / Induced (2x coil +1) (per WBS 42- Power Supplies and Quench Protection) • max Layer to layer = 240V inductive during fast dump • Coil to Ground >7.5 kV - Quench Voltage - Test to 2x+1=16kV dc hipot (per WBS 42- Power Supplies and Quench Protection) • Ground wrap to case (with ground point lifted) 1 kV dc	• dc High Potential Meter • Tan-Delta Meter • Impulse test system	• dc Hipot $\Rightarrow$ 10 kV production test $\Rightarrow$ 0.01 mA current trip • Impulse $\Rightarrow$ 2.9 kV • Tap 6 $\Rightarrow$ 11.3 kV AC $\Rightarrow$ 60 Hz
5. Structure Insulation Integrity	TFMSRD §3.2.1.5	B & W and TPX Site	• Ground Plane Insulation Integrity • Component Insulation Integrity	• After coil and component installation • After Delivery to TPX Site	• TF assembly to other assemblies >1 kV • Helium Isolators >10 KV in GHe.	• High Potential Meter	• dc Hipot $\Rightarrow$ 10 kV production test $\Rightarrow$ 0.01 mA current trip
6. Flow Impedance	TFMSRD §3.1.2.9	B & W and TPX Site	• Verify pressure drop through winding does not exceed limit. • Verify pancake variability does not exceed limit	• After Delivery to TPX Site	• 5 ATM inlet - 2-3 ATM outlet GC He • 28 g/s in TF coil GC He (7g/s through each winding) • Gas Argon Test (11 ATM drop @ 1.71 SCFM per Kelly Dixon)	• Flow meters • Pressure transducers • Pressurized Argon supply	• Flow meter $\Rightarrow$ 2 SCFM, .01 res • Pressure Transducer $\Rightarrow$.05 psi
7. Helium Leak Testing	TFMSRD §3.3.1.2	B & W and TPX Site	• Weld Integrity	• Throughout manufacturing • After Delivery to TPX Site	• TBD	• Helium Leak Test system • Enclosures	• TBD
8. Octant Level Cold Tests	TBD	TBD	• Cold magnet, structure, and instrumentation data	• After completion of Octant assembly	• TBD	• Cold test facility with TBD capabilities	• TBD
9. System Level Tests	TBD	TPX Site	• Final assembly certification / calibration	• After system assembly is complete	• TBD	• Operational data, power, and control systems	• TBD

Figure 3.3.3-5 TF Magnet System Assembly and Verification

3.4 TF Local I&C Implementation (WBS 135)

To be provided by LLNL

- 3.4.1 Design
- 3.4.2 Manufacturing
- 3.4.3 Verification

3.5 TF Bus and Leads Implementation (WBS 136)

To be provided by LLNL

- 3.5.1 Design
- 3.5.2 Manufacturing
- 3.5.3 Verification

3.6 TF Assembly, Installation, and Verification

To be developed in Phase II

- 3.6.1 Magnet Handling and Installation
- 3.6.2 TF Bus and Leads Installation
- 3.6.3 TF Local I&C Integration
- 3.6.4 Magnetic Field Mapping
- 3.6.5 Magnet System Verification

4. OPERATIONS

Following installation and checkout, operation of the TF Magnet System will not require more than two persons per shift to monitor magnet diagnostics and protection systems at the TF Local I&C console. During magnet cool-down, initial operation, and periodic systems testing, no more than five operators and technicians will be required to monitor and evaluate the performance of the TF Magnet System. The instrumentation points that will be monitored are listed in Section 3.5 of this document. No magnet system control variables are anticipated.

TF Magnet System operating personnel will be drawn from a pool of personnel who are experienced in laboratory operations and magnet testing. No special operator training will be required.

Suppliers of TF Magnet Subsystems will provide installation procedures together with subassemblies and parts, and will oversee assembly, installation, and initial verification of their components. TPX construction personnel will require no special training to accomplish magnet installation and integration activities. The installation procedures will provide sufficient information for repair actions, as required.

5. MAINTENANCE

5.1 Scheduled Maintenance Activities

The TF magnet and bus assemblies will not require routine maintenance. TF Local I&C will require periodic calibration and maintenance at an interval of not less than six months. Scheduled maintenance for any other purpose shall not exceed one week per three operating weeks averaged over a 32-week run period.

The following items will require routine inspection:

1. The annular space between the nose of the TF coil and the central solenoid (CS). This area should be visually inspected to monitor movement of the TF coil and to ensure that there is no contact between the TF and CS stack. The noses of the TF coils will also be inspected to ensure that the insulation is intact.
2. The helium manifolds, insulators, filters, and instrumentation at the top of the coil cases. These items will be visually inspected to look for leaks and damage to the tubes, isolators, insulation, and instrumentation wires.

Access to the magnet lead boxes will be provided through the Cryostat in accordance with TPX-ICDP-1315-0001 for replacement of sensors or repair of electrical or fluid connections. Access will also be provided within the cryostat for inspection and tightening of TF magnet assembly bolts.

5.2 Maintenance Equipment and Parts

There is no special maintenance equipment required for the TF magnet system. Repair parts and modules for TF Magnet System components will be recommended by the component suppliers for procurement determination by the TPX Project. Spare parts and modules will be stocked at the TPX site as required to meet the availability requirements.

Facilities and equipment for handling, assembly, and installation of TF Magnet System components at the TPX site will be as specified in TPX-ICDP-1317-0001.

The modular TF magnet design allows recovery from a coil failure with minimum backup hardware, since the magnet octants are interchangeable. In the event of coil failure, an entire four-coil TF quadrant, including the vacuum vessel segment, would be replaced. Replacement involves removal of the cryostat, upper PF coils, buses, and coolant lines. The lower PF coils would be lowered onto the test cell floor. The in-vessel manipulator would remove activated plasma facing components and separate the vacuum vessel sector from the remainder of the torus with a plasma torch. The TF magnet section is separated at its bolted joints. A replacement magnet module would then be aligned and bolted in place, and the vacuum vessel segment would be bolted in position and seal welded. Reinstallation of the PF coils, utilities, and cryostat would complete the operation, in a time estimated to be approximately one year.

5.3 Remote Maintenance Category I and II Equipment Lists

There is no required remote maintenance for the TF coils. Bolts and resistive joints between the TF quadrants can be disconnected without radiation protection.

6. REFERENCES

6.1 TPX Project Documents

- 6.1.1 TPX General Requirements Document, TPX-RQMT-GRD, Rev 1, dated May 12, 1995 (not released)
- 6.1.2 Tokamak System Requirements Document, TPX-RQMT-SRD, draft A, dated May 9, 1995 (not released)
- 6.1.3 TPX Structural and Cryogenic Design Criteria, TPX-STND-001 Rev 1, dated January 17, 1995
- 6.1.4 TPX Seismic Design Criteria, TPX-STND-002, Rev 0, dated November 22, 1994
- 6.1.5 TPX Grounding for Equipment and Personnel Safety, TPX-STND-004, Rev 0, dated July 25, 1994
- 6.1.6 TPX Material Properties Handbook, TPX-STND-005, Rev 0, 94-950615-PPPL-IZatz-02
- 6.1.7 TPX Project Management Plan, TPX-PLAN-PMP, Rev 2, 91-950215-PPPL-JSchmidt-02
- 6.1.8 TPX Environmental, Safety, and Health Protection Implementation Plan, Annex II to the TPX PMP, Rev 0 dated July 21, 1993

6.2 Industry and Military Specifications and Standards

- 6.2.1 MIL-STD-490A, Military Standard Specification Practices, dated June 4, 1985
- 6.2.2 MIL-STD-1629A Procedure for Performing a Failure Modes Effects and Criticality Analysis, with Notice 1 dated June 7, 1983
- 6.2.3 ASME Boiler and Pressure Vessel Code

6.3 LLNL Documents

- 6.3.1 LLNL TPX Quality Assurance Plan, TPX-LLNL-PLAN-002, Rev 1, dated January 17, 1995
- 6.3.2 TPX TF Superconductor Specification, TPX-SPEC-132-0001, Rev 0, dated TBD (to be prepared)

6.4 Subcontractor Documents

- SDRL 01 Design Control Process
- SDRL 02 Drawing System and Standards
- SDRL 03 Project Management Plan
- SDRL 13 Quality Assurance Plan
- SDRL 14 Configuration Management and Change Control Plan
- SDRL 17 Magnet System Specification, TPX-SPEC-013-0001
- SDRL 18 Interface Control Documents

TF Magnet System (WBS 13) to Vacuum Vessel (WBS 12) Interface
Control Document, TPX-ICDP-1213-0001

TF Magnet System (WBS 13) to PF Magnet System (WBS 14) Interface
Control Document, TPX-ICDP-1314-0001

TF Magnet System (WBS 13) to Cryostat (WBS 15) Interface Control
Document, TPX-ICDP-1315-0001

TF Magnet System (WBS 13) to Tokamak Support Structure (WBS 16)
Interface Control Document, TPX-ICDP-1316-0001

TF Magnet System (WBS 13) to Tokamak Assembly (WBS 17) Interface
Control Document, TPX-ICDP-1317-0001

TF Magnet System (WBS 13) to Field Error Control Coils (WBS 19)
Interface Control Document, TPX-ICDP-1319-0001

TF Magnet System (WBS 13) to Vacuum Pumping System (WBS 34)
Interface Control Document, TPX-ICDP-1334-0001

TF Magnet System (WBS 13) to Electrical Power System (WBS 42)
Interface Control Document, TPX-ICDP-1342-0001

TF Magnet System (WBS 13) to Instrumentation and Control System
(WBS 61) Interface Control Document, TPX-ICDP-1361-0001

TF Magnet System (WBS 13) to Cryogenic Equipment (WBS 72) Interface
Control Document, TPX-ICDP-1372-0001

TF Magnet (WBS 133) to TF Local Instrumentation and Control (WBS
135) Interface Control Document, TPX-ICDS-133/135-0001

TF Magnet (WBS 133) to TF Bus and Leads (WBS 136) Interface Control
Document, TPX-ICDS-133/136-0001

TF Local Instrumentation and Control (WBS 135) to TF Bus and Leads
(WBS 136) Interface Control Document, TPX-ICDS-135/136-0001

- SDRL 19 Design Plan

SDRL 20 Configuration Item Specifications

TPX TF Coil Specification, TPX-SPEC-133-0001

TPX Coil Winding Equipment Specification, TPX-SPEC-133-0002

TPX Coil Reaction Equipment Specification, TPX-SPEC-133-0003

TPX Coil VPI Equipment Specification, TPX-SPEC-133-0004

SDRL 21 Materials and Processes Selection

SDRL 22 Critical Equipment Drawings, Specifications, and Procurement Plans

SDRL 23 FMECA

SDRL 25 Long Lead Materials and Equipment

SDRL 29 Analysis Results

Design Models Registry

TF Magnet Electromagnetic Analysis

Global Structural Analysis of the TF Structure

Comparison of Bolted/Welded and All-Bolted TF Structures

TF Winding Pack Analysis

Development of 3D S2 Glass Preforms for Shear Stress Mitigation

Interim 3D Baseline Shear Stress Analysis

TF Magnet Test Cell Interconnections

TF Winding Pack Quench Analysis and Quench Detection Sensitivity

TF Winding Pack Steady-State Thermal Hydraulic Analysis

Preliminary Case Cooling Design Analysis

SDRL 30 Engineering Drawings

SDRL 31 Magnet Sensors

SDRL 32 Coil Assembly Documentation

SDRL 33 Coil Verification Testing Plan

SDRL 34 Material and Component Testing Plan

SDRL 36 Integrated Magnet Plan

SDRL 37 Mfg Research Plans and Results

A. Reaction R&D Report

B. Conductor Bending R&D Report

SDRL 45 Acceptance Test Plan

Handling Devices and Equipment for Components, B&W M41-100, dated 11/91

Nuclear Equipment Engineering Standard for Shipping Equipment, B&W NEE-1, Rev 2
dated May 29, 1981

TOKAMAK PHYSICS EXPERIMENT (TPX)

**TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE**

Contract B235308

SDRL 17

Magnet System Specification

TPX-SPEC-013-00001

August 18, 1995

13-950811-BW-RBatchelder-02

Babcock & Wilcox
Accelerator & Magnet Systems
PO Box 785
Mt. Athos Road
Lynchburg, VA 24505

Approved for Submittal by:
C.M. Weber, TPX Project Mgr.

PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**TOROIDAL FIELD MAGNET
SYSTEM REQUIREMENTS DOCUMENT**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-SPEC-013-0001
REVISION 0**

Prepared for: the University of California
Lawrence Livermore National Laboratory
Subcontract B235308, SDRL 17

Prepared by: the Babcock & Wilcox Company
NNFD, Accelerator and Magnet Systems
Mt. Athos Road, Lynchburg, VA 24505

The original document is on file at B&W.

It was prepared and signed by:	R.R. Batchelder, B&W Systems Engineering
It was approved and signed by:	C.M. Weber, B&W TPX Project Manager
It was approved and signed by:	G.A. Deis, LLNL Magnet WBS Manager
It was approved and signed by:	E.W. Southwick, LLNL QA Engineer
It was approved and signed by:	J.D. Levine, TPX Project ES&H Manager
It was approved and signed by:	F.A. Malinowski, TPX Project QA Manager
It was approved and signed by:	W. T. Reiersen, TPX Systems Engineering Manager
It was approved and signed by:	J.C. Sinnis, TPX Project Engineer
It was approved and signed by:	G.H. Neilson, TPX Physics Manager
It was approved and signed by:	J.A. Schmidt, TPX Project Director

SIGNATURE SHEET

Prepared by:
R.R. Batchelder, B&W Systems Engineering

Approved by:
C.M. Weber, B&W TPX Project Manager

Approved by:
G.A. Deis, LLNL Magnet WBS Manager

Approved by:
E.W. Southwick, LLNL QA Engineer

Approved by:
J.D. Levine, TPX Project ES&H Manager

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Approved by:
G.H. Neilson, TPX Physics Manager

Approved by:
J.A. Schmidt, TPX Project Director

DOCUMENT CHANGE RECORD

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1. SCOPE

This document specifies the performance, design, documentation, and quality assurance requirements for the Toroidal Field (TF) Magnet System, part of the Tokamak Physics Experiment to be installed at the Princeton Plasma Physics Laboratory (PPPL). The purpose of the TPX is to demonstrate long-pulse and continuous tokamak operating modes with high plasma pressure and enhanced confinement.

The function of the TF Magnet System is to provide the toroidal magnetic field necessary to confine the plasma in all operating modes. The TF Magnet System encloses an internal vacuum vessel, and supports and interacts with poloidal field (PF) magnets, field error correction coils, and their leads and buses.

The required toroidal field is provided by 16 superconducting coils spaced nominally 22.5° apart. The system includes cooling provisions to maintain the superconducting coils at the required low temperature under the influence of nuclear and thermal radiation; electrical connections to the magnet power supply; and instrumentation and controls to protect the magnets under upset conditions and to provide engineering data for magnet performance analysis.

The TF magnet will be delivered as octants or quadrants, and will be assembled into the system configuration at PPPL. The midplane of the TF magnet is the geometric reference for assembly of other tokamak systems, and will be appropriately marked.

Requirements for the TF Magnet System are derived from the TPX General Requirements Document through subordinate documents. Appendix 10.1 provides traceability from the provisions of Section 3 of this specification to their source.

2. APPLICABLE DOCUMENTS

The following documents of exact issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this specification, the following order of precedence shall prevail:

1. TPX Program Documents marked with an asterisk * (2.1.1 - 2.1.5 and 2.1.24 - 2.1.26)
2. This specification
3. Other documents.

2.1 TPX Program Documents

- 2.1.1* TPX General Requirements Document, TPX-RQMT-GRD, Rev 1, dated May 12, 1995
- 2.1.2* TPX System/Segment Specification, TPX-RQMT-SRD, draft A, dated May 9, 1995 (not released)
- 2.1.3* TPX Structural and Cryogenic Design Criteria, TPX-STND-001 Rev 1, dated January 17, 1995
- 2.1.4* TPX Seismic Design Criteria, TPX-STND-002, Rev 0, dated December 22, 1994
- 2.1.5* TPX Grounding for Equipment and Personnel Safety, TPX-STND-004, Rev 0, dated July 25, 1994
- 2.1.6 TPX TF Superconductor Specification, TPX-SPEC-132-0001, Rev 0, dated TBD (to be prepared)
- 2.1.7 TPX TF Coil Specification, TPX-SPEC-133-0001, Rev 0, dated August 11, 1995
- 2.1.8 TPX Coil Winding Equipment Specification, TPX-SPEC-133-0002, Rev 0, dated August 7, 1995
- 2.1.9 TPX Coil Reaction Equipment Specification, TPX-SPEC-133-0003, Rev 0, dated August 2, 1995
- 2.1.10 TPX Coil VPI Equipment Specification, TPX-SPEC-133-0004, Rev 0, dated August 7, 1995
- 2.1.11 TF Magnet System (WBS 13) to Vacuum Vessel (WBS 12) Interface Control Document, TPX-ICDP-1213-0001
- 2.1.12 TF Magnet System (WBS 13) to PF Magnet System (WBS 14) Interface Control Document, TPX-ICDP-1314-0001
- 2.1.13 TF Magnet System (WBS 13) to Cryostat (WBS 15) Interface Control Document, TPX-ICDP-1315-0001
- 2.1.14 TF Magnet System (WBS 13) to Tokamak Support Structure (WBS 16) Interface Control Document, TPX-ICDP-1316-0001

- 2.1.15 TF Magnet System (WBS 13) to Tokamak Assembly (WBS 17) Interface Control Document, TPX-ICDP-1317-0001
- 2.1.16 TF Magnet System (WBS 13) to Field Error Control Coils (WBS 19) Interface Control Document, TPX-ICDP-1319-0001
- 2.1.17 TF Magnet System (WBS 13) to Vacuum Pumping System (WBS 34) Interface Control Document, TPX-ICDP-1334-0001
- 2.1.18 TF Magnet System (WBS 13) to Electrical Power System (WBS 42) Interface Control Document, TPX-ICDP-1342-0001
- 2.1.19 TF Magnet System (WBS 13) to Instrumentation and Control System (WBS 61) Interface Control Document, TPX-ICDP-1361-0001
- 2.1.20 TF Magnet System (WBS 13) to Cryogenic Equipment (WBS 72) Interface Control Document, TPX-ICDP-1372-0001
- 2.1.21 TF Magnet (WBS 133) to TF Local Instrumentation and Control (WBS 135) Interface Control Document, TPX-ICDS-133/135-0001
- 2.1.22 TF Magnet (WBS 133) to TF Bus and Leads (WBS 136) Interface Control Document, TPX-ICDS-133/136-0001
- 2.1.23 TF Local Instrumentation and Control (WBS 135) to TF Bus and Leads (WBS 136) Interface Control Document, TPX-ICDS-135/136-0001
- 2.1.24*LLNL TPX Quality Assurance Plan, TPX-LLNL-PLAN-002, Rev 1, dated January 17, 1995
- 2.1.25*TPX Environmental, Safety, and Health Implementation Plan, TPX-PLAN-ESH, Rev 0, dated July 21, 1993 (Annex II to the TPX Project Management Plan)
- 2.1.26*TPX Material Properties Handbook, TPX-STND-005, draft dated June 15, 1995 (not released)

2.2 Military and Industrial Specifications and Standards

- 2.2.1 MIL-STD-490A, Military Standard Specification Practices, dated June 4, 1985
- 2.2.2 MIL-STD-1629A Procedure for Performing a Failure Modes Effects and Criticality Analysis, with Notice 1 dated June 7, 1983
- 2.2.3 ASME Boiler and Pressure Vessel Code
- 2.2.4 B&W M41-100, Handling Devices and Equipment for Components, dated November, 1991
- 2.2.5 B&W Nuclear Equipment Engineering Standard for Shipping Equipment, NEE-1, Rev 2 dated May 29, 1981

3. REQUIREMENTS

3.1 Prime Item Definition

3.1.1 Prime Item Diagrams

- a. The TF Magnet System shall be comprised of a TF magnet assembly, TF Local Instrumentation and Control, and TF Leads and Buses. The functional relationships of the TF Magnet subsystems and other tokamak systems shall be as shown in Figure 3-1.
- b. The TF magnet shall be comprised of 16 coils in a toroidal configuration at a nominal spacing of 22.5° , as shown in Figure 3-2. Each coil shall be fabricated of Nb₃Sn superconducting cable-in-conduit-conductor (CICC), and shall consist of 12 pancakes of 7 turns each for a total of 84 turns. [SRD §3.7.3]
- c. The TF coils shall be assembled into two-coil octant modules as shown on Drawing D-1334000. Prior to installation in the tokamak, two-coil modules shall be assembled into four-coil quadrants as shown on Drawing D-1332100. Clear openings and electrical break planes shall be as shown on drawing, D-1332000. [SRD §3.7.3]
- d. The TF magnet coils shall be connected in two electrical interleaves of eight coils each in series, as shown on Drawing D-1333101. [SRD §3.7.3]
- e. The TF magnet and TF leads and bus shall be connected to cryogenic fluid cooling lines as shown on the cryogenic schematic, Drawing C-1333102.

3.1.2 Interface Definition

3.1.2.1 Vacuum Vessel Interface (WBS 12)

- a. The TF Magnet is assembled around the Vacuum Vessel, which contains the tokamak plasma. The TF Magnet structure shall provide penetrations for neutral beams, diagnostic instruments, and vacuum pumping ports, as specified in TPX-ICDP-1213-0001 (reference 2.1.11).
- b. The TF Magnet shall operate under the influence of thermal and nuclear radiation emitted by the plasma and moderated by the Vacuum Vessel, as specified in TPX-ICDP-1213-0001 (reference 2.1.11). The Vacuum Vessel shall include thermal insulation and shall contain borated water in its walls to moderate the radiant fluxes.
- c. The TF Magnet structure shall support the Vacuum Vessel quadrants during installation and assembly of the tokamak as described in TPX-ICDP-1317-0001 (reference 2.1.15). During magnet operation, there shall be no direct mechanical, fluid, or electrical connection between the TF Magnet System and the Vacuum Vessel.

Figure 3-1 TF Magnet System Functional Relationships

Figure 3-2 TF Magnet Mechanical Configuration

3.1.2.2 PF Magnet System Interfaces (WBS 14)

- a. The TF Magnet structure shall provide mechanical support and alignment for the PF Magnets as specified in TPX-ICDP-1314-0001 (reference 2.1.12). The nominal tokamak midplane, defined as a horizontal plane which passes through the elevation of maximum plasma radial extent, shall coincide with the plane of symmetry of the PF system under operating conditions. [GRD §1.1]
- b. The TF Magnet shall operate under the influence of the dynamic magnetic fields created by the PF Magnets in accordance with TPX-ICDP-1314-0001 (reference 2.1.12). The maximum displacements and loads at the PF mounting points during assembly, cooldown, operation, and disruption conditions shall be as specified in the ICD. The PF Magnet shall include compliant supports as necessary to limit load transfer due to relative displacements.
- c. The maximum temperature differences and heat transfer at the PF mounting points shall be as specified in TPX-ICDP-1314-0001 (reference 2.1.12).
- d. There shall be no direct fluid or electrical connection between the TF and PF Magnets. The PF Magnet shall include electrical isolators to limit the flow of current across the interface.

3.1.2.3 Cryostat Interfaces (WBS 15)

- a. The TF Magnet and Bus and Leads shall operate in the vacuum and thermal environment provided by the Cryostat, and shall have outgassing and leak rate limits as specified in TPX-ICDP-1315-0001 (reference 2.1.13).
- b. The TF electrical leads and instrumentation lines shall penetrate the cryostat as specified in TPX-ICDP-1314-0001 (reference 2.1.13). The TF bus ducts and leads provide a vacuum closure for, and are evacuated by the Cryostat.
- c. Other than bus penetrations and instrumentation feed-throughs, there shall be no direct mechanical, fluid, or electrical connection between the TF Magnet System and the Cryostat.

3.1.2.4 Tokamak Support Structure Interface (WBS 16)

- a. The TF Magnet shall be mechanically supported by the Tokamak Support Structure in accordance with TPX-ICDP-1316-0001 (reference 2.1.14). The Support Structure shall include slip joints to limit load transfer due to relative radial displacements.
- b. There shall be no direct fluid or electrical interface between the TF Magnet and the Support Structure. The Support Structure shall include electrical and thermal isolators to limit the flow of current or heat across the interface.

3.1.2.5 Field Error Correction Coil Interfaces (WBS 19)

- a. The TF Magnet shall provide clearance for, and shall mechanically support the Field Error Correction coils in accordance with TPX-ICDP-1316-0001 (reference 2.1.16).
- b. The TF Magnet shall interact magnetically and thermally with the Field Error Correction coils in accordance with TPX-ICDP-1316-0001 (reference 2.1.16). The

FECC shall contain thermal isolation mounts that react the maximum interface loads, and that limit the flow of heat across the interface.

- c. There shall be no direct fluid or electrical connection between the TF Magnet and the Field Error Correction coils. The FECC shall contain electrical isolators to prevent the flow of current across the interface.
- d. The Field Error Correction coils shall be capable of compensating the residual TF magnet field errors as specified in 3.2.1.2.

3.1.2.6 Vacuum Pumping System Interface (WBS 34)

- a. The TF Magnet structure shall include penetrations for vacuum pumping ducts, as specified in TPX-ICDP-1334-0001 (reference 2.1.17).
- b. The TF Magnet shall operate under the influence of thermal and nuclear radiation emitted by the vacuum pumping ducts, as specified in TPX-ICDP-1334-0001 (reference 2.1.17). The pumping ducts shall include thermal insulation to moderate the radiant fluxes.
- c. The TF Magnet shall enable transfer of vacuum vessel support to the vacuum pumping ducts during installation and assembly of the tokamak as described in TPX-ICDP-1317-0001 (reference 2.1.15). During magnet operation, there shall be no direct mechanical, fluid, or electrical connection between the TF Magnet System and the vacuum pumping ducts.

3.1.2.7 Electrical Power System Interfaces (WBS 42)

- a. The Electrical Power System shall supply direct current to the TF Magnet in accordance with TPX-ICDP-1342-0001 (reference 2.1.18). The power supply shall provide compensation for EMF induced in the TF magnet from field variations associated with plasma initiation, beta change transients, and equilibrium control in accordance with the Tokamak System Requirements Document (reference 2.1.2), §3.2.1.4.1.3. The current supplied to the TF magnet shall be constant within $\pm \text{TBD}\%$ between plasma initiation and discharge. [SRD §3.2.1.4.1.2]
- b. The Electrical Power System shall include switches and dump resistors capable of isolating and safely dissipating the energy in the TF Magnet in response to a signal from TF Magnet Local Instrumentation and Control, as specified in TPX-ICDP-1342-0001 (reference 2.1.18).
- c. The TF Magnet System shall include cryogenic buses, current leads, and vacuum boxes that interface with the Electrical Power System at room temperature, in accordance with TPX-ICDP-1342-0001 (reference 2.1.18).
- d. The Electrical Power System shall provide a single point ground for TF Magnet System components in accordance with TPX-ICDP-1342-0001 (reference 2.1.18) and TPX-STND-004 (reference 2.1.5).
- e. Other than room-temperature connections, the TF Magnet System shall have no direct mechanical or fluid interfaces with the Electrical Power System.

3.1.2.8 Instrumentation and Control Interfaces (WBS 61)

- a. The TF Magnet System shall include Local Instrumentation and Control capable of sensing and processing data for magnet protection and engineering evaluation. Data shall be exchanged between the TF Local I&C and Central I&C in accordance with TPX-ICDP-1361-0001 (reference 2.1.19).
- b. TF Magnet Local I&C shall be capable of sensing a quench or other upset, and transmitting a signal to the Electrical Power System for coil protection, in accordance with TPX-ICDP-1342-0001 (reference 2.1.18).
- c. TF Magnet Local I&C shall receive and process fault indication signals from the Central I&C in accordance with TPX-ICDP-1361-0001 (reference 2.1.19), and shall transmit a signal to the Electrical Power System to initiate coil protection, in accordance with TPX-ICDP-1342-0001 (reference 2.1.18), in the event of an upset condition.
- d. TF Magnet Local I&C electronics shall be located and powered in accordance with TPX-ICDP-1317-0001 (reference 2.1.15).
- e. Other than Cryostat electrical feed throughs, cable and cabinet supports, and electrical power and data connections, the TF Magnet System Local I&C shall have no direct mechanical or fluid interfaces with other tokamak systems.

3.1.2.9 Cryogenic Equipment Interfaces (WBS 72)

- a. TPX Cryogenic Equipment shall supply the TF Magnet with gaseous and supercritical helium. The fluid circuits, steady state temperature and flow conditions, and cool-down and warm-up profiles shall be in accordance with TPX-ICDP-1372-0001 (reference 2.1.20).
- b. The TF Magnet shall apply flow impedance to the fluids supplied by the Cryogenic Equipment within limits specified in TPX-ICDP-1372-0001 (reference 2.1.20).
- c. The effects of a quench in a TF Magnet coil on the Cryogenic Equipment, and the response of the Cryogenic Equipment to a quench, shall be as defined in TPX-ICDP-1372-0001 (reference 2.1.20).
- d. The TF Magnet System interfaces with the Cryogenic Equipment fluid lines shall be at welded connections to header feeds adjacent to the cryogenic manifolds, and at the gas-cooled lead vacuum boxes in the spreading room, in accordance with TPX-ICDP-1372-0001 (reference 2.1.20). The TF Magnet shall provide attachment points for electrically-isolated fluid line support brackets, which are part of the Cryogenic Equipment. Electrical isolators between current-carrying elements and the fluid lines; filters; and fluid flow, pressure, and temperature instrumentation shall be part of the TF Magnet System.
- e. Other than fluid connections and support brackets, there shall be no mechanical or electrical interfaces between the Cryogenic Equipment and the TF Magnet System.

3.1.2.10 Tokamak Assembly Interfaces (WBS 17)

- a. The TF Magnet shall include provisions for temporary quadrant support during installation, and fiducials and access for alignment to the facility datum in accordance with TPX-ICDP-1317-0001 (reference 2.1.15).
- b. Requirements for handling and supporting TF Magnet quadrants shall be in accordance with TPX-ICDP-1317-0001 (reference 2.1.15), which specifies unit weight, envelope, pickup details, and responsibilities for special handling and support equipment. The quadrants shall be stored and handled in accordance with Magnet Shipping and Storage Criteria and Magnet Handling Procedures to be developed by the magnet manufacturer.
- c. The TF Magnet shall include provisions for installation and support of the vacuum vessel quadrants (using tooling provided by the assembly element) during transfer and installation in the test cell, and access for alignment and welding of vacuum vessel joints, in accordance with TPX-ICDP-1317-0001 (reference 2.1.15).
- d. The TF Magnet shall be capable of being assembled using tools and utilities such as air and electric power, as defined in TPX-ICDP-1317-0001 (reference 2.1.15).

3.1.3 Major Component List

The following items are components of the TF Magnet System that will be developed separately, and that have independently verifiable performance requirements.

3.1.3.1 Superconductor (WBS 132)

- a. The TF Magnet coils shall be fabricated using Nb₃Sn cable-in-conduit superconductor in accordance with Specification TPX-SPEC-132-0001 (reference 2.1.6).
- b. The TF Bus shall be fabricated using NbTi cable-in-conduit superconductor in accordance with Specification TPX-SPEC-TBD (reference TBD)

3.1.3.2 TF Magnet (WBS 133)

- a. The TF Magnet shall be comprised of 16 coils and supporting structure as defined in this specification. Each TF Magnet Coil shall be designed and fabricated in accordance with TPX-SPEC-133-0001 (reference 2.1.7).
- b. The TF Magnet shall include sensors as specified in 3.2.1.6 and leads interfacing with TF Local I&C in accordance with TPX-ICDS-133/135-0001 (reference 2.1.21).
- c. Electrical connections between the TF Magnet and the superconducting bus shall be in accordance with TPX-ICDS-133/136-0001 (reference 2.1.22).

3.1.3.3 TF Local Instrumentation and Control (WBS 135)

- a. The TF Local I&C Subsystem shall include sensor interfaces, data acquisition systems, quench detection systems, and interfaces to other systems as described herein. The locations of Local I&C electronic assemblies, cable routings, and feed-throughs shall be in accordance with TPX-ICDP-1317-0001 (reference 2.1.15).

- b. The quench protection signal and grounding interfaces between TF Local I&C and the TF Power System shall be as defined by TPX-ICDP-1342-0001 (reference 2.1.18).
- c. The data interface between TF Local I&C and TPX Central I&C shall be as defined by TPX-ICDP-1361-0001 (reference 2.1.19).
- d. The sensor signal interface between TF Local I&C and the TF Magnet shall be as defined by TPX-ICDS-133/135-0001 (reference 2.1.21).
- e. The sensor signal interface between TF Local I&C and the TF Bus and Leads shall be as defined by TPX-ICDS-135/136-0001 (reference 2.1.23).

3.1.3.4 TF Bus and Leads (WBS 136)

- a. The TF Bus and Leads shall include a superconducting bus, current leads, and related cooling provisions that connect the TF Magnet to the electrical power system. The routing and installation details of the TF Bus and Leads shall be in accordance with TPX-ICDP-1317-0001 (reference 2.1.15).
- b. The TF Magnet System shall include current leads making the transition from cryogenic to room temperature. The room-temperature electrical connection between the TF leads and the electrical power system shall be in accordance with TPX-ICDP-1342-0001 (reference 2.1.18).
- c. The electrical connections between the TF Bus and the TF Magnet shall be in accordance with TPX-ICDS-133/136-0001 (reference 2.1.22).
- d. The TF Bus and Leads shall contain sensors and leads interfacing with TF Local I&C System in accordance with TPX-ICDS-135/136-0001 (reference 2.1.23).

3.1.3.5 TPX Coil Winding Equipment

The TF coil shall be fabricated with the TPX Coil Winding Equipment, which shall be designed and fabricated in accordance with specification TPX-SPEC-133-0002 (reference 2.1.8).

3.1.3.6 TPX Coil Reaction Equipment

The TF coil shall be fabricated with the TPX Coil Reaction Equipment, which shall be designed and fabricated in accordance with specification TPX-SPEC-133-0003 (reference 2.1.9).

3.1.3.7 TPX Coil VPI Equipment

The TF coil shall be fabricated with the TPX Coil Vacuum Pressure Impregnation Equipment, which shall be designed and fabricated in accordance with specification TPX-SPEC-133-0004 (reference 2.1.10).

3.2 Characteristics

3.2.1 Performance

3.2.1.1 Operating States

- a. The TF Magnet System shall provide a steady-state toroidal magnetic field during plasma startup and operation in the high current and low current double-null and single null reference scenarios, and in the flexibility space defined in the Tokamak System Requirements Document, §3.2.1.4.1.3 (reference 2.1.2). [GRD §1.1, §1.2]
- b. The TF Magnet System shall be designed for a bi-directional toroidal field in all reference scenarios, with the plasma current in either the same direction as the toroidal field, or in the opposite direction. [GRD §1.2.3; SRD §3.2.1.4.1.1] The plasma current density shall be as defined in the Tokamak System Requirements Document, §TBD (reference 2.1.2). {incorporate 93-950209-LLNL-RBulmer-01 in SRD}
- c. The TF Magnet System shall be designed for steady state operation with H and D plasmas, with peak neutron source rates of 7.5×10^{16} DD neutrons/sec and 2.25×10^{15} DT neutrons/sec. The TF Magnet System shall provide not less than 1 sec of operation with a DT plasma at peak neutron source rates of 6.4×10^{16} DD neutrons/sec and 5.3×10^{18} DT neutrons/sec. [GRD §2.1 and §2.5] Associated heat loads on the TF magnet shall be as specified in the Tokamak System Requirements Document, §TBD (reference 2.1.2). {incorporate memos 13-940517-MIT-RPillsbury-01; 94-940329-PPPL-SLiew-01; and 94-940415-PPPL-SLiew-01 in the SRD}
- d. The TF Magnet system shall withstand without damage a rapid loss of vacuum within the cryostat due to venting or leakage. [source TBD]

3.2.1.2 Magnetic Field

- a. The TF Magnet System shall provide a minimum toroidal field strength of 4.0 T in the tokamak midplane at a major radius of 2.25 m, with an operating current of 33.5 kA. [GRD §1.2; SRD §3.2.1.4.1.2]
- b. The peak-to-average variation (ripple) in toroidal field strength over the plasma cross section shall not exceed 0.4%. The plasma cross section shall be the area defined by the reference surface in the Tokamak System Requirements Document, §3.2.1.4.1.4.1 (reference 2.1.2). [GRD §1.6; SRD §3.2.1.4.1.2]
- c. The radial components of magnetic field on the plasma surface due to the non-axisymmetric effects of TF coil misalignment, TF coil leads and cross-overs, TF magnetic materials, and the TF bus shall not exceed the following values:

$$\delta B_{r,1} \leq \text{TBD Gauss}$$

$$\delta B_{r,2} \leq 0.32 \text{ Gauss}$$

$$\delta B_{r,m,1} \leq 0.64 \text{ Gauss, } m = 1, 3, 4$$

$$\delta B_{r,4,2} \leq 0.64 \text{ Gauss}$$

$$\delta B_{r,m,2} \leq 1.28 \text{ Gauss, } m = 3, 5$$

where $\delta B_{r\ m,n}$ are the Fourier components of radial field strength with poloidal harmonic number "m" and toroidal harmonic number "n". The plasma surface shall be as defined in the Tokamak System Requirements Document, §3.2.1.4.1.4.1 (reference 2.1.2). [GRD §1.7; SRD §3.2.1.4.1.4.1]

3.2.1.3 Quench Stability

- a. The TF Magnet System shall satisfy the superconductor design requirements specified in the TPX Structural and Cryogenic Design Criteria (reference 2.1.3, §II-2), in the operating modes of 3.2.1.1, given the cooling fluid conditions of 3.1.2.9, the operating current and field of 3.2.1.2, and the dynamic fields associated with equilibrium control as specified in the System Requirements Document, §3.2.1.4.1.3.4 (reference 2.1.2). [GRD §4.2; SRD §3.2.1.4.1.2]
- b. The TF Magnet System shall be capable of ramping without quenching from zero to operating current, and from operating current to zero, in periods not to exceed 10 minutes. [GRD §1.9.3] The ramp profiles shall be as defined in the Electrical Power ICD, TPX-ICDP-1342-0001 (reference 2.1.18).
- c. The TF Magnet System shall withstand, without quenching, plasma disruptions as defined in the Tokamak System Requirements Document, §3.2.1.4.3 (reference 2.1.2). [GRD §1.10]
- d. The TF Magnet System shall withstand without damage a fast or slow dump in accordance with the Electrical Power ICD, TPX-ICDP-1342-0001 (reference 2.1.18).

3.2.1.4 High Voltage Breakdown

- a. Performance of the TF Magnet System electrical insulation shall be in accordance with the TPX Structural and Cryogenic Design Criteria, §II-3 (reference 2.1.3). [GRD §4.2]
- b. The TF Magnet System electrical power circuits shall withstand the maximum quench voltage in accordance with the TPX Structural and Cryogenic Design Criteria, §II-1.1 (reference 2.1.3). [GRD §4.2]

3.2.1.5 Electrical Isolation and Grounding

- a. The TF magnet structure shall include resistive breaks between octants to provide toroidal resistance for development of the startup voltage. [GRD §1.8.4]
- b. Each octant of the TF magnet assembly shall be electrically isolated from all other assemblies (except for coil power and instrumentation connections), and grounded with a single point ground in accordance with TPX Grounding for Equipment and Personnel Safety (reference 2.1.5). The leakage current between assemblies in air shall be not more than 1 mA at a standoff voltage 1 kV, with the single point ground lifted. [source TBD]

3.2.1.6 Instrumentation and Quench Detection

- a. The TF Magnet System shall contain instrumentation and processors capable of detecting a quench event in any coil, in coil connections, or in the bus and leads, and initiating a dump of the energy in the magnet in accordance with the requirements of

the TPX Structural and Cryogenic Design Criteria, § II-1.4 and §II-1.5 (reference 2.1.3). [GRD §4.2, SCDC §II-1.4 and §II-1.5]

- b. The TF current leads shall contain voltage taps and flow sensors for active control of cooling gas flow by the Cryogenic Equipment. [SDD §2.4.4.3]
- c. The TF magnet shall include strain gauges on the coil cases and magnet support structure to verify the peak stresses predicted by analysis; and magnetic field sensors in each magnet quadrant to measure the toroidal field strength and polarity. [SDD §2.4.1]

3.2.1.7 Cool-Down and Warm-Up

- a. Given the cool-down conditions of 3.1.2.9, the TF Magnet System shall be capable of cool-down from room temperature to operating temperature within 120 hours. [SRD §3.2.1.2]
- b. Given the warm-up conditions of 3.1.2.9, the TF magnet shall be capable of warm-up from operating temperature to room temperature within 60 hours. [SRD §3.2.1.2]
- c. The magnet coils and buses shall be capable of carrying current in the normal conducting state to expedite warm-up. [SRD §3.2.1.2]
- d. Given the cooling fluid conditions of 3.1.2.9, the TF Magnet System shall be capable of being cooled to operating temperature within 12 hours following a quench. [SRD §3.2.1.2]

3.2.1.8 Operating Cycles and Useful Life

- a. The TF Magnet System shall be designed for an operating life of 10 years. [GRD 2.4]
- b. Within the operating life, the TF Magnet System shall be designed for the following total number of cycles:
 - 300 cool-down/warm-up cycles [GRD §2.4; SRD §3.2.1.2]
 - 6,000 charge/discharge cycles [GRD §2.4; SRD §3.2.1.4.1.2]
 - **TBD** hours total time in which the TF magnet is energized. [source **TBD**]
 - 30,000 plasma pulses [GRD §2.4]
 - 5 million sec total operating time (with plasma current) [GRD §2.4]
 - 2 million sec D operating time [GRD §2.4]
 - 50 quench cycles [SRD §3.2.1.2]
 - 15,000 plasma disruption cycles. [GRD §1.10; SRD §3.2.1.4.3]
- c. Within any year, the TF Magnet System shall be designed for 10% of the lifetime number of cycles. [GRD 2.3]
- d. The foregoing life and cycles shall apply only to operation prior to the injection of tritium into the system. [GRD 2.3]

3.2.2 *Physical Characteristics*

3.2.2.1 Size and Weight

- a. The size and weight of the assembled TF magnet and its components shall be consistent with the interface requirements defined in 3.1.2.
- b. The size and weight of the TF magnet coil, octant, and quadrant assemblies shall be consistent with the transportability requirements of 3.2.6, and the handling and assembly requirements of 3.1.2.9.
- c. The size and shape of the TF coil shall be as defined in the TF coil specification, TPX-SPEC-133-0001 (reference 2.1.7).

3.2.3 *Reliability and Availability*

- a. The probability of failure of TF magnet components that are not accessible without magnet disassembly shall be less than **TBD** within the operating life, as a goal. Such components shall include the coil windings and support structure. [GRD §3.1]
- b. The availability of the TF Magnet System shall be not less than 97.0%. Availability is defined as $100\% \times (1 - N)$, where N is the ratio of the number of shots in which the TF Magnet System failed to meet its performance requirements to the number of shots that could be achieved in an operational period. Delays due to low probability events, such as a TF coil replacement, shall not be included in availability verification. [GRD §3.2; SRD §3.2.5.3]
- c. The shot reliability of the TF Magnet System, defined as the probability of TF Magnet System operation without malfunction for the duration of a shot, shall be not less than 0.9958. [GRD §3.3; SRD §3.2.5.1.2]
- d. The foregoing reliability and availability criteria do not apply after injecting tritium into the plasma. [GRD §3.1]

3.2.4 *Maintainability*

- a. Maintainability of the TF Magnet System shall be consistent with the foregoing availability requirement, applied to components accessible outside the TF magnet assembly. [GRD §3.4]
- b. TF magnet components within the cryostat, including connections in the magnet lead box, shall be accessible for disassembly and repair within two weeks following tokamak shutdown. [GRD §3.4; SRD §3.2.5.2]
- c. The TF magnet shall be capable of physical disassembly to permit replacement of a failed coil, following a shutdown period of up to one year during which activated in-vessel components are remotely removed. [GRD §3.4; SRD §3.2.5.2]
- d. The foregoing maintainability criteria do not apply after injection of tritium. [GRD §3.4; SRD §3.2.5.2]

3.2.5 *Environmental Conditions*

3.2.5.1 Shipping and Storage Environments

TF Magnet System components shall be designed to withstand the following non-operating conditions during shipment and storage:

- a. Temperature: -31 to 49°C (-24 to 120°F); surfaces exposed to sunlight shall withstand a maximum temperature of 71°C (160°F) [MIL-STD-810E, Methods 501 and 502]
- b. Relative humidity: 10% to 95%, non-condensing
- c. Transportation load: per B&W Standard NEE-1 (reference 2.2.5)

3.2.5.2 Operating Environments

- a. The TF magnet structures shall be designed for combined operating loads in accordance with the TPX Structural and Cryogenic Design Criteria (reference 2.1.3, §I-1 and §I-2), at operating temperatures determined from the coolant flow of TPX-ICDP-1372-0001 (reference 2.1.20) and the heat loads of 3.2.1.1.
- b. The TF magnet assembly shall be designed for the combined nuclear dose of the TPX Structural and Cryogenic Design Criteria (reference 2.1.3, §II-2.12).
- c. TF magnet components within the cryostat shall be designed to operate in a vacuum as defined in TPX-ICDP-1315-0001 (reference 2.1.13).
- d. TF Magnet System components outside the cryostat shall be designed to operate in a laboratory environment, with a temperature range of 15 to 30°C (60 to 86°F), and relative humidity of 20 to 90%.
- e. All TF Magnet System components shall be designed in accordance with the TPX Seismic Design Criteria (reference 2.1.4)

3.2.6 *Transportability*

- a. TF magnet coils shall be designed for transportability between fabrication sites by truck or dolly.
- b. The TF magnet shall be designed for transportability as octants or quadrants between fabrication sites and to the TPX site by truck, rail, or barge.
- c. All other TF components shall be transportable by truck with commercial packaging.
- d. System components shall be protected in shipment and storage by covers to prevent direct exposure to rainfall, snow, or blowing sand or dust. Volumes not accessible for cleaning after delivery shall be protected by securely fastened covers or caps.
- e. The exposed TF magnet coil leads shall be protected by fixtures at all times to ensure compliance with the strain requirement of the TPX Structural and Cryogenic Design Criteria, §II-2.11. [SCDC §II-2.11]

3.3 Design and Construction

3.3.1 Materials, Processes, and Parts

3.3.1.1 Material Selection

- a. Materials selected for use in the TF magnet shall be compatible with the strength, temperature, vacuum, impurity control, magnetic permeability, and activation requirements of the intended application. Except as authorized by the Project, material properties shall be as specified in the TPX Material Properties Handbook, TPX-STND-005 (reference 2.1.26). [GRD §1.13]
- b. The magnetic permeability of materials used in the TF magnet, with the exception of the superconductor sheath, shall not exceed 1.02. [GRD §1.13]
- c. The residual radioactivity of materials used in the TF magnet shall not exceed Class A low level waste limits as defined in 10 CFR 61, after exposure to the lifetime dosage specified in 3.2.5.2. [GRD §6.0]

3.3.1.2 Weldments

- a. The design of manufacturing and field weldments shall conform to the intent of the ASME Boiler and Pressure Vessel Code, Section VIII (reference 2.2.3).
- b. Welding procedures and operator qualifications shall conform to the intent of the ASME Boiler and Pressure Vessel Code, Section IX (reference 2.2.3).

3.3.2 Reserved

3.3.3 Nameplates and Product Marking

- a. All unit assemblies shall be permanently identified by a nameplate containing the unit descriptor, part number, serial number, supplier, and month of manufacture. Magnet assemblies shall be identified in accordance with [TBD by SIS contractor].
- b. Replaceable components shall be clearly marked with identifiers traceable to the circuit schematics, parts lists, and other documentation used for maintenance.
- c. Internal wiring shall be identified by wire number traceable to the circuit schematics and wiring diagrams used for maintenance. Terminal blocks shall be provided with markings corresponding to those of the wire and wiring diagrams.

3.3.4 Workmanship [MIL-STD-454N, Requirement 9]

- a. The TF Magnet System shall be fabricated and assembled in a workmanlike manner, and shall be accurate in dimensions and alignment of parts with respect to the tolerances on the design drawings.
- b. Assemblies and parts thereof shall be cleaned of smudges; loose, spattered or excess solder; weld metal; metal chips and mold release agents; or any other foreign material which might detract from the intended operation, function or appearance.

- c. Screws, nuts and bolts shall show no evidence of cross threading, mutilation, or detrimental or hazardous burrs, and shall be firmly secured. Fastener installation shall conform to the specified type and tightness or torquing.
- d. Wires and cables shall be positioned or protected to avoid contact with rough or irregular surfaces and sharp edges to avoid damage to insulation, conductors, or adjacent parts.
- e. Shielding on wires and cables shall be secured in a manner to prevent contact or shorting of exposed current-carrying parts. The ends of shielding or braid shall be secured to prevent fraying.
- f. Harnesses and cable containment shall be neat in appearance, uniformly applied and positioned to retain critical form factors and breakout locations. The containment means shall not cause the wire or cable insulation to deform so that performance characteristics are adversely affected.
- g. There shall be no evidence of burns, abrading or pinch marks in the insulation that could cause short circuits or current leakage.

3.3.5 Interchangeability [MIL-STD-454N, Requirement 7]

Design tolerances shall permit parts and assemblies of the same part number to be used as replacement items without detracting from the specified performance of the parent item.

3.3.6 Safety

The TF Magnet System shall be designed in accordance with the TPX Environmental Safety and Health Implementation Plan (reference 2.1.25).

3.3.7 Human Factors

- a. The design of the TF Magnet System and its manufacturing and test methods shall be consistent and compatible with human capabilities to manufacture and test the system and its components in a repeatable, efficient and safe manner. Mature and proven tooling and methods shall be used to the extent possible.
- b. The design of TF Magnet System controls shall permit system operation with minimal operator fatigue and possibility of human error.

3.3.8 Structural Integrity

3.3.8.1 TF Magnet Structures

- a. Components of the TF magnet shall withstand combined loads and environmental conditions as specified in 3.2.5 and the TPX Structural and Cryogenic Design Criteria, §I-2.0 (reference 2.1.3), including manufacturing and transportation stress and preload, without damage or degradation in performance during the useful life of the system.
- b. Applied stresses shall not exceed the limits specified in the TPX Structural and Cryogenic Design Criteria, §I-3 and §I-4 (reference 2.1.2).

3.3.8.2 Support Equipment

- a. Stands, dollies, and lifting equipment used to support end item fabrication and handling shall be design in accordance with the LLNL Mechanical Engineering Design Safety Standards (reference 2.2.4).
- b. Temporary support and lifting points on the end item assemblies shall be designed to carry 3 x the supported dead weight.

3.4 Documentation

3.4.1 Specifications

Specifications shall be developed by the Supplier to establish the derivation, flow-down, and control of requirements as follows:

- a. Critical Item specifications for the TF Conductor, TF Coil, and coil manufacturing equipment items listed in 3.1.3, in accordance with MIL-STD-490, Type B2, as a guide (reference 2.2.1).
- b. Process specifications defining process control parameters and limits, in accordance with MIL-STD-490, Type D, as a guide (reference 2.2.1).
- c. Material specifications for materials not controlled by established government or industry standards, in accordance with MIL-STD-490, Type E, as a guide (reference 2.2.1).

3.4.2 Drawings

- a. TF Magnet drawings shall be prepared for delivery in accordance with Project standards and procedures to describe all components of the system, its installation and interconnections. Such drawings shall include detail part drawings, assembly drawings, electrical and fluid schematics, and wiring diagrams adequate for fabrication of the end item, and for installation and maintenance of the system.
- b. TF Magnet drawings shall be maintained under configuration control to define the as-built configuration of the delivered system.

3.4.3 Plans

- a. Plans for verification of the conformance of TF Magnet System components to the provisions of this specification shall be prepared by the component suppliers. Such plans shall include engineering plans for verification by analysis or demonstration, and plans for verification by inspection and test, in accordance with the Quality Conformance Matrix, Table 4-1.
- b. Plans for transportation, handling, and installation of TF Magnet System components shall be prepared by the component suppliers. Such plans shall detail the methods, procedures, and tooling required for integration of the component into the tokamak by TPX construction personnel.

3.5 Logistics

3.5.1 Maintenance

- a. TF magnet and bus assemblies shall not require routine maintenance. Access to the magnet lead boxes shall be provided through the Cryostat in accordance with TPX-ICDP-1315-0001 (reference 2.1.13) for replacement of sensors or repair of electrical or fluid connections. Access shall also be provided for inspection and tightening of TF magnet assembly bolts. [source **TBD**]
- b. TF Local I&C shall require periodic calibration and maintenance at an interval of not less than six months. [SDD §2.4.8]
- c. Scheduled maintenance for any other purpose shall not exceed one week per three operating weeks averaged over a 32 week run period. [GRD §3.5]

3.5.2 Supply

- a. Repair parts and modules for TF Magnet System components shall be recommended by the component suppliers for procurement determination by the TPX Project. Spare parts and modules shall be stocked at the TPX site as required to meet the availability requirements of 3.2.3.

3.5.3 Facilities and Facility Equipment

- a. Facilities and equipment for handling, assembly, and installation of TF Magnet System components at the TPX site shall be as specified in TPX-ICDP-1317-0001 (reference 2.1.15).

3.6 Personnel and Training

3.6.1 Personnel

- a. Following installation and checkout, operation of the TF Magnet System shall not require more than two persons per shift to monitor magnet diagnostics and protection systems. [SDD §2.4.7]
- b. During magnet cool-down, initial operation, and periodic systems testing, no more than five operators and technicians shall be required to monitor and evaluate the performance of the TF Magnet System. [SDD §2.4.7]

3.6.2 Training

- a. TF Magnet System operating personnel shall be drawn from a pool of personnel who are experienced in laboratory operations and magnet testing. No special operator training shall be required.
- b. Suppliers of TF Magnet System components shall oversee installation and initial verification of their components. TPX construction personnel shall require no special training to accomplish magnet installation and integration activities.

3.7 Major Component Characteristics

3.7.1 TF Magnet Coil

- a. The TF magnet coil configuration shall be as defined in 3.1.1.b and 3.1.3.2.
- b. The TF magnet coils shall meet the quench stability requirements of 3.2.1.3 in any operating state.
- c. The TF magnet coil shall meet the high voltage breakdown requirements of 3.2.1.4.
- d. The TF magnet coils shall be compatible with the cool-down and warm-up requirements of 3.2.1.7, and the quench recovery requirement of 3.2.1.3.e.
- e. The TF magnet coil shall meet the structural integrity criteria of 3.3.8 in any operating state, and in the operating life specified in 3.2.1.8.

3.7.2 TF Magnet Structure

- a. The TF magnet structure shall be compatible with the envelopes of interfacing systems, and shall provide attachment points as specified in 3.1.2.
- b. The TF magnet structure shall support and align the 16 TF magnet coils such that the magnetic field requirements of 3.2.1.2 are met in any operating state.
- c. The TF magnet structure shall support the PF coils and FEC coils such that the operational displacements defined in TPX-ICDP-1314-0001 (reference 2.1.12) and TPX-ICDP-1319-0001 (reference 2.1.16) are met in any operating state.
- d. The TF magnet structure shall provide electrical isolation and grounding as specified in 3.2.1.5.
- e. The TF magnet structure shall contain cooling fluid passages to limit heat transfer to the coils, and shall be compatible with the cool-down and warm-up requirements of 3.2.1.7.
- f. The TF magnet structure shall meet the structural integrity criteria of 3.3.8 in any operating state, and in the operating life specified in 3.2.1.8.

3.7.3 TF Local Instrumentation and Control

- a. TF Local I&C shall provide sensor interfaces, signal conditioners (excitation sources and signal amplifiers), voltage isolation, cabling, and data acquisition systems in accordance with the requirements of 3.1.3.3 and 3.2.1.6.
- b. TF Local I&C shall provide magnet and bus quench detection in accordance with the requirements of 3.2.1.3.d and 3.2.1.6.
- c. TF Local I&C shall provide an interface with TPX Central I&C for receipt of fault indicators from other systems, and for magnet status display and data archiving in accordance with 3.1.2.8.

3.7.4 TF Bus and Leads

- a. The TF Bus and Leads shall be configured in accordance with 3.1.3.4. The TF Bus conduit shall provide a vacuum closure of the Cryostat in accordance with 3.1.2.3.
- b. The TF Bus and Leads shall meet the quench stability requirements of 3.2.1.3 in any operating state.
- c. The TF Bus and Leads shall meet the high voltage breakdown requirements of 3.2.1.4.
- d. The TF Bus and Leads shall be compatible with the cool-down and warm-up requirements of 3.2.1.7, and the quench recovery requirement of 3.2.1.3.e.
- e. The TF Bus and Leads shall meet the structural integrity criteria of 3.3.8 in any operating state, and in the operating life specified in 3.2.1.8.

3.8 Precedence

- a. The order of precedence of this specification relative to referenced documents shall be as defined in 2.0.
- b. The relative weights of performance requirements are:
 - 1. Electrical breakdown and insulation integrity.
 - 2. Quench stability and protection in all operating states.
 - 3. Magnetic field requirements.
 - 4. Electrical isolation requirements.
 - 5. Cool-down and warm-up requirements.

4. QUALITY ASSURANCE PROVISIONS

4.1 General

4.1.1 *Responsibility for Tests and Inspections*

- a. LLNL shall be responsible to the Project for verification of compliance with all requirements of this specification. LLNL shall perform a cold test of a prototype TF magnet coil; and shall verify the TF Local I&C and TF Bus and Leads by analysis, demonstration, inspection, and test as defined in the Quality Conformance Matrix.
- b. The TF magnet supplier shall be responsible for verification of conformance to magnet performance and design requirements of this specification by analysis and demonstration; component, material, and process qualification tests; and magnet coil electrical tests at room temperature. The TF magnet supplier will support prototype testing at LLNL and system testing at PPPL.
- c. The TF superconductor supplier(s) shall be responsible for verification of conformance to the requirements of the applicable specifications for strand, cable, and finished CICC.
- d. The MIT Plasma Fusion Center shall be responsible for verification of magnet operating, disruption, and fault loads; heat loads; and quench performance by analysis of the integrated tokamak.
- e. PPPL shall be responsible for assembly of the tokamak and verification of TF Magnet System requirements by integrated systems testing.

4.1.2 *Special Verifications*

- a. Documentation shall be prepared and delivered, including analyses and qualification test or demonstration records, that verify conformance to requirements inherently determined by the design of the TF Magnet. Such verifications shall demonstrate adequate operating margins to assure the operational reliability of the system.
- b. Compliance with the reliability, availability, and maintainability requirements of 3.2.3 and 3.2.4 shall be verified as follows:
 - 1) A Failure Modes Effects and Criticality Analysis shall be performed using MIL-STD-1629 as a guide (reference 2.2.2).
 - 2) The probability of failure in each failure mode shall be estimated; those modes with a significant probability of occurrence relative to the reliability or availability requirements will be identified as critical failure modes.
 - 3) Component failure rates or material strength distributions shall be derived from historical data where available; where such data are not available or are not relevant, tests shall be performed on a sufficient number of components or material samples in environmental profiles similar to the TPX application to provide the statistical basis for verification.
- c. Conformance to the magnet stability and high voltage breakdown requirements shall be verified in test of a single prototype coil in a cryogenic facility provided by LLNL.

4.1.3 Quality Assurance System

Documentation of conformance to the requirements specified herein shall be provided, prepared within a system that assures the integrity of the data furnished. The system shall include provisions for inspection, maintenance of test and measuring equipment, control of non-conforming material, and record-keeping in accordance with the LLNL TPX Quality Assurance Plan (reference 2.1.24).

4.2 Quality Conformance Matrix

Verification of the requirements of this specification shall be in accordance with the Quality Conformance Matrix, Table 4-1. The indicated methods of verification are defined as follows:

- a. Analysis: verification by calculation or simulation, including computer modeling based on established material or component characteristics.
- b. Demonstration: observation of functional operation at ambient; or review of design drawings and specifications; or review of data for similar components and applications.
- c. Inspection: measurements of dimensions, time, electrical parameters, etc., performed at ambient with general-purpose instruments; or review of records from prior conformance verification.
- d. Test: verification by physically exercising a component or system under appropriate loads and operating conditions, including measurement and analysis of performance data.

Table 4-1
TF Magnet System Quality Conformance Matrix

<i>Paragraph</i>	<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>	<i>N/A</i>
3.1 Item Definition					x
3.1.1 Prime Item Diagrams			x		
3.1.2 Interface Definition					x
3.1.2.1 Vacuum Vessel Interface (WBS 12)		x	x	S	
3.1.2.2 PF Magnet System Interfaces (WBS 14)		x	x	S	
3.1.2.3 Cryostat Interfaces (WBS 15)		x	x	S	
3.1.2.4 Tokamak Support Structure Interfaces (WBS 16)		x	x	S	
3.1.2.5 Field Error Correction Coil Interfaces (WBS 19)		x	x	S	
3.1.2.6 Vacuum Pumping System Interfaces (WBS 34)		x	x	S	
3.1.2.7 Electrical Power System Interfaces (WBS 42)		x		S	
3.1.2.8 Instrumentation and Control Interfaces (WBS 61)		x		S	
3.1.2.9 Cryogenic Equipment Interfaces (WBS 72)		x		S	
3.1.2.10 Tokamak Assembly Interfaces (WBS 95)		x			

Table 4-1 (Cont'd)
TF Magnet System Quality Conformance Matrix

<i>Paragraph</i>	<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>	<i>N/A</i>
3.1.3 Critical Component List					X
3.1.3.1 TF Conductor (WBS 132)			X -		
3.1.3.2 TF Magnet (WBS 133)		X			
3.1.3.3 TF Local Instrum. and Control (WBS 135)		X			
3.1.3.4 TF Bus and Leads (WBS 136)		X			
3.1.3.5 TPX Coil Winding Equipment		X	--		
3.1.3.6 TPX Coil Reaction Equipment		X			
3.1.3.7 TPX Coil VPI Equipment		X			
3.2 Characteristics					X
3.2.1 Performance					X
3.2.1.1 Operating States	X			S	
3.2.1.2 Magnetic Field	X			S	
3.2.1.3 Quench Stability	X			P, S	
3.2.1.4 High Voltage Breakdown	X			A, P, S	
3.2.1.5 Electrical Isolation and Grounding	X	X		A, P, S	
3.2.1.6 Instrumentation and Quench Detection		X		A, P, S	
3.2.1.7 Cool-down and Warm-up	X			S	
3.2.1.8 Operating Cycles and Useful Life	X				
3.2.2 Physical Characteristics					X
3.2.2.1 Size and Weight		X			
3.2.3 Reliability and Availability	X				
3.2.4 Maintainability		X			
3.2.5 Environmental Conditions					X
3.2.5.1 Shipping and Storage Environments	X	X			
3.2.5.2 Operating Environments	X				
3.2.6 Transportability		X			
3.3 Design and Construction					X
3.3.1 Materials, Processes, and Parts					X
3.3.1.1 Material Selection		X			
3.3.1.2 Weldments	X		X		
3.3.2 Reserved					X
3.3.3 Nameplates and Product Marking			X		
3.3.4 Workmanship			X		
3.3.5 Interchangeability of Components		X			
3.3.6 Safety		X			
3.3.7 Human Factors		X			
3.3.8 Structural Integrity					X
3.3.8.1 TF Magnet Structures	X				
3.3.8.2 Support Equipment	X				
3.4 Documentation					X
3.4.1 Specifications			X		
3.4.2 Design Drawings			X		
3.4.3 Plans			X		
3.5 Logistics					X
3.5.1 Maintenance		X			
3.5.2 Supply		X			
3.5.3 Facilities and Facility Equipment		X			
3.6 Personnel and Training					X
3.6.1 Personnel		X			
3.6.2 Training		X			

Table 4-1 (Cont'd)
TF Magnet System Quality Conformance Matrix

<i>Paragraph</i>	<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>	<i>N/A</i>
3.7 Major Component Characteristics					x
3.7.1 TF Magnet Coil	x		-	A, P, S	
3.7.2 TF Magnet Structure	x			S	
3.7.3 TF Local Instrumentation and Control		x		A, S	
3.7.4 TF Bus and Leads	x	x	—	S	

Testing code: A - Factory Acceptance Test; P - Prototype Test; S - Tokamak Systems Test

5. PREPARATION FOR DELIVERY

- a. The TF magnet shall be delivered as specified in 3.1.3.4 and 3.2.6, in accordance with Shipping and Storage Criteria and Handling Procedures prepared by the magnet manufacturer.
- b. All other components of the TF Magnet System shall be packaged in accordance with good commercial practice for delivery to the TPX site.

6. NOTES

6.1 Definitions of Acronyms

ASME	American Society of Mechanical Engineers
CICC	Cable-In-Conduit Conductor
CFR	Code of Federal Regulations
D, DD	Deuterium
DOE	Department of Energy
DT	Deuterium-Tritium
EMF	Electromotive Force
GRD	General Requirements Document
I&C	Instrumentation and Control
ICD	Interface Control Document
LLNL	Lawrence Livermore National Laboratory
PF	Poloidal Field
PPPL	Princeton Plasma Physics Laboratory
SCDC	Structural and Cryogenic Design Criteria
SCN	Specification Change Notice
SRD	System Requirements Document; System/Segment Specification
TBD	To Be Determined
TF	Toroidal Field
TPX	Tokamak Physics Experiment
VPI	Vacuum Pressure Impregnation
WBS	Work Breakdown Structure

10. APPENDIX

10.1 Sources of Requirements

The requirements of Section 3 herein have the sources indicate in the following list:

<i>Para.</i>	<i>Requirement</i>	<i>Source of Requirement</i>
3.1	Prime Item Definition	N/A
3.1.1	Prime Item Diagrams	B&W; SRD §3.7.3
3.1.2	Interface Definition	N/A
3.1.2.1	Vacuum Vessel Interface (WBS 12)	B&W
3.1.2.2	PF Magnet System Interfaces (WBS 14)	B&W; GRD §1.1
3.1.2.3	Cryostat Interfaces (WBS 15)	B&W
3.1.2.4	Support Structure Interfaces (WBS 16)	B&W
3.1.2.5	Field Error Corr. Coil Interfaces (WBS 19)	B&W
3.1.2.6	Vac. Pumping System Interfaces (WBS 34)	B&W
3.1.2.7	Electrical Pwr System Interfaces (WBS 42)	B&W
3.1.2.8	Instr. and Control Interfaces (WBS 61)	B&W
3.1.2.9	Cryogenic Equipment Interfaces (WBS 72)	B&W
3.1.2.10	Tokamak Assembly Interfaces (WBS 95)	B&W
3.1.3	Major Component List	N/A
3.1.3.1	TF Conductor (WBS 132)	B&W
3.1.3.2	TF Magnet (WBS 133)	B&W
3.1.3.3	TF Local Instrum. and Control (WBS 135)	B&W
3.1.3.4	TF Bus and Leads (WBS 136)	B&W
3.1.3.5	TPX Coil Winding Equipment	B&W
3.1.3.6	TPX Coil Reaction Equipment	B&W
3.1.3.7	TPX Coil VPI Equipment	B&W
3.2	Characteristics	N/A
3.2.1	Performance	N/A
3.2.1.1	Operating Modes	GRD §1.1, §1.2, §2.1, §2.5; SRD §3.2.1.4.1.1, §3.2.1.4.1.3, refs TBD
3.2.1.2	Magnetic Field	GRD §1.2, §1.6, §1.7; SRD §3.2.1.4.1.2, §3.2.1.4.1.4
3.2.1.3	Quench Stability	GRD §1.9.3, §1.10 §4.2; SRD §3.2.1.2, §3.2.1.4.1.2, §3.2.1.4.3; SCDC §II-1, II-2
3.2.1.4	High Voltage Breakdown	GRD §4.2; SCDC §II-1.1, II-3
3.2.1.5	Electrical Isolation and Grounding	GRD §1.8.4; SRD ref TBD
3.2.1.6	Instrumentation and Quench Detection	
3.2.1.7	Cool-down and Warm-up	SRD §3.2.1.2
3.2.1.7	Operating Cycles and Useful Life	GRD §2.3, §2.4, §1.10; SRD §3.2.1.2, §3.2.1.4.1.2, §3.2.1.4.3
3.2.2	Physical Characteristics	N/A
3.2.2.1	Size and Weight	B&W
3.2.3	Reliability and Availability	GRD §3.1, §3.2, §3.3; SRD §3.2.5.1.2, §3.2.5.3
3.2.4	Maintainability	GRD §3.4, §3.5; SRD §3.2.5.2
3.2.5	Environmental Conditions	N/A
3.2.5.1	Non-Operating Environments	B&W; MIL-STD-810E Methods 501 and 502
3.2.5.2	Operating Environments	SCDC §I-1, §I-2, §II-2.12; B&W
3.2.6	Transportability	B&W
3.3	Design and Construction	N/A
3.3.1	Materials, Processes, and Parts	N/A
3.3.1.1	Material Selection	GRD §1.13, §6.0
3.3.1.2	Weldments	B&W
3.3.2	Reserved	N/A
3.3.3	Nameplates and Product Marking	B&W
3.3.4	Workmanship	MIL-STD-454N Reqt 9

<i>Para.</i>	<i>Requirement</i>	<i>Source of Requirement</i>
3.3.5	Interchangeability of Components	MIL-STD-454N Reqt 7
3.3.6	Safety	PPPL ES&H Plan
3.3.7	Human Factors	B&W
3.3.8	Structural Integrity	N/A
3.3.8.1	Environmental Profiles	B&W; SCDC §I-2
3.3.8.2	Allowable Stresses	SCDC §I-3, I-4; B&W
3.3.8.3	Support Equipment	LLNL ME Design Safety Standards
3.4	Documentation	N/A
3.4.1	Specifications	B&W
3.4.2	Design Drawings	B&W
GRD	General Requirements Document	
SCDC	Structural and Cryogenic Design Criteria	
SRD	System/Segment Specification	

10.2 TF Magnet Drawings

E-1332000	TF Magnet Structural Penetrations
D-1332100	Magnet System Envelopes
D-1333101	TF Hemisphere Charging Circuit
C-1333102	TF Magnet Octant Hydraulic Circuit
D-1334000	TF Octant Assembly

PRELIMINARY

THIS IS A PRELIMINARY DRAWING. DO NOT
USE FOR CONSTRUCTION OR FABRICATION.

PROJECT NO.	B225308
DATE	10/11/82
DESIGNED BY	W. J. WILSON
CHECKED BY	W. J. WILSON
APPROVED BY	W. J. WILSON
PROJECT NAME	TOROIDAL FIELD MAGNET STRUCTURAL PENETRATIONS
PROJECT NO.	1339000

141,700	141,700
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SECTION A - A
2X SCALE

PRELIMINARY

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NOTES:

1. REMOVE ALL BURRS, FINISHED PRODUCT SHALL BE FREE FROM FOREIGN MATTER.
2. MATERIAL:
3. MARK PART NUMBER & SERIAL NUMBER PER BAW SPEC. DWS-XXXXX.

SECTION A-A

PRELIMINARY

THIS IS A CAD GENERATED DRAWING, DO NOT MAKE MANUAL REVISIONS OR ALTERATIONS.

CONTRACT NO. B235308

BABCOCK & WILCOX
LYNCHBURG, VIRGINIA 24503

APPROVALS DATE TITLE

R. E. GRIT 4-25-92

R. E. GRIT

A. ANTAYA

TF OCTANT ASSEMBLY

SIZE CASE CODE D 31.399 DRAWING NO. D-1334000 REV PD

SCALE SHEET 3

TOLERANCES OF WHOLE NUMBERS	TOLERANCES OF DECIMALS
±.005	±.005
±.001	±.001
±.0005	±.0005

1. SMALL ALL BUMP EDGES
2. DIM. TO MAX FILL IN - 1000
3. DIM. TO MAX FILL IN - 1000
4. DIM. TO MAX FILL IN - 1000

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT AND MANUFACTURE

Contract B235308

SDRL 18
Interface Control Documents
August 18, 1995
13-950811-BW-RSmith-03

Babcock & Wilcox
Accelerator & Magnet Systems
PO Box 785
Mt. Athos Road
Lynchburg, VA 24505

Approved for Submittal by:
C.M. Weber, TPX Project Mgr.

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1213-0001 Rev. A Page 1 of 5
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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Vacuum Vessel (WBS 12)**

TPX-ICDP-1213-0001 REVISION A

Date: 7 July 1995

Prepared By:
B. R. Smith
Babcock & Wilcox Company

Concurred By: _____
C. M. Weber
TF Magnet Project Manager

Concurred By: _____
TBD
Vacuum Vessel Project Manager

Approved By: _____
G. Deis, LLNL
Magnet WBS Manager

Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1213-0001
		Rev. A Page 2 of 5

DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First Update based on ICD format changes and comments from B. Pedrotti/LLNL.	A	7 July 1995

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1213-0001 Rev. A Page 3 of 5
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1.0 SCOPE

This document provides a detailed description of the Toroidal Field (TF) Magnet System (WBS 13) to Vacuum Vessel (WBS 12) Interfaces for the TPX. The Vacuum Vessel is located within the TF Magnet assembly and contains the tokamak plasma.

The Vacuum Vessel has vertical and radial ports that provide access for plasma heating, current drive, vacuum pumps, and diagnostic equipment between the TF coils through openings in the TF structure.

2.0 APPLICABLE DOCUMENTS

The following documents of the issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

2.1.1 TPX Toroidal Field Magnet System Description Document, dated March 16, 1993

2.1.2 Vacuum Vessel System Description Document, dated March 2, 1993

2.1.3 TPX Grounding for Equipment and Personnel Safety, 94-9440429-PPPL/WRauch-01, dated May 26, 1994

2.1.4 [PPPL/LLNL Drawings--TBD]

2.2 Specifications and Standards

TBD

2.3 Contractor Documents

2.3.1 TPX-ICDP-1317-0001: TF Magnet (WBS 13) to Tokamak Assembly and Installation (WBS 17) Interface Control Document

3.0 RESPONSIBILITIES

3.1 TF Magnet Element (WBS 133): prepare and maintain this document. Design and fabricate the TF Magnet in conformance with the requirements stated herein.

3.2 Vacuum Vessel Element (WBS 12): design and fabricate the Vacuum Vessel in conformance with the requirements stated herein.

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1213-0001 Rev. A Page 4 of 5
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4.0 INTERFACE DEFINITION

4.1 Functional Interfaces

- a. The Vacuum Vessel shall provide a thermal barrier between the tokamak plasma at 10⁹ K and the TF Magnet at 5 K.
- b. The Vacuum Vessel shall moderate the nuclear radiation emitted by the plasma to a level that is tolerable by the TF Magnet.
- c. There shall be no direct mechanical, fluid, or electrical interfaces between the Vacuum Vessel and the TF Magnet. Mechanical interfaces during tokamak assembly are defined in the TF Magnet to Tokamak Assembly and Installation ICD (reference 2.3.1).

4.2 Mechanical Interfaces

4.2.1 Envelopes

- a. The envelope of the TF Magnet shall be as represented in a TBD TF Magnet 3-D Solid Model.
- b. The Vacuum Vessel envelope (Drawing TBD) shall include allowances for assembly and alignment tolerances and differential thermal contraction. The Vacuum Vessel including super insulation shall not be less than TBD mm from the TF Magnet structure.
- c. The TF Magnet structure shall contain penetrations to clear the plasma heating and current drive, diagnostic instrumentation, and vacuum pumpout ports as shown in Drawing TBD.
- d. There shall be no contact between the Vacuum Vessel and the TF Magnet during any operating condition or at temperature extremes.

4.2.2 Thermal Interfaces

- a. The maximum temperature at the outside of any Vacuum Vessel insulation facing the TF Magnet shall be 350 C during bakeout. The operating temperature of the Vacuum Vessel shall not exceed 150 C and the operating temperature of the TF Magnet shall be 5 K (-260C).
- b. The Vacuum Vessel insulation blanket shall limit the total radiation heat loss to the TF Magnet to TBD.

4.2.3 Nuclear Radiation

- a. The Vacuum Vessel walls shall limit the nuclear radiation incident on the TF Magnet to TBD.

4.3 Fluid Interfaces

None.

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1213-0001
		Rev. A Page 5 of 5

4.4 Electrical Interfaces

4.4.1 Magnetic Fields

- a. The magnetic field at the wall of the Vacuum Vessel due to the TF Magnet shall not exceed 4 Tesla.

4.4.2 Isolation

- a. The TF Magnet system and the Vacuum Vessel shall be electrically isolated from each other and separately grounded in accordance with the TPX Grounding Specification (reference 2.1.3).

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the Vacuum Vessel and TF Magnet Elements, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with LLNL and the TPX Systems Integration Element.

TF Magnet to Vacuum Vessel Interface Verification Matrix
(Method: A=Analysis, D=Demonstration, I=Inspection, T=Test)

Requirement	Responsibility	Method
The Vacuum Vessel shall provide a thermal barrier between the tokamak plasma at 10 ⁹ K and the TF Magnet at 5 K	WBS 12	A
There shall be no direct mechanical, fluid, or electrical interfaces between the Vacuum Vessel and the TF Magnet	WBS 12/13	I
The envelope of the TF Magnet shall be as represented in a TBD TF Magnet 3-D Solid Model	WBS 13	A
The Vacuum Vessel envelope (Drawing TBD) shall include allowances for assembly and alignment tolerances and differential thermal contraction	WBS 12	A/D
The Vacuum Vessel including super insulation shall not be less than TBD mm from the TF Magnet structure	TBD	D
The TF Magnet structure shall contain penetrations to clear the plasma heating and current drive, diagnostic instrumentation, and vacuum pumpout ports as shown in Drawing TBD	WBS 13	A/D
There shall be no contact between the Vacuum Vessel and the TF Magnet during any operating condition or at temperature extremes	TBD	A/T
The maximum temperature at the outside of any Vacuum Vessel insulation facing the TF Magnet shall be 350 C during bakeout	WBS 12	A
The Vacuum Vessel insulation blanket shall limit the total radiation heat loss to the TF Magnet to TBD	WBS 12	A/D
The Vacuum Vessel walls shall limit the nuclear radiation incident on the TF Magnet to TBD	WBS 12	A/T
The magnetic field at the wall of the Vacuum Vessel due to the TF Magnet shall not exceed 4 Tesla	WBS 13	A/T

VESSEL TOLERANCES
90° SOUTHEAST SEGMENT
FILE: TOL.TOLVSS90SE
DRAWING ONE

90. DEVELOPED ELEVATION VIEW

SOUTHEAST SEGMENT
PLAN VIEW
SCALE: 1/16

JOINT

JOINT

JOINT

JOINT

OUTSIDE OF OUTSIDE SHELL

AREA OF PORTS TO BE SUBTRACTED FROM TOTAL AREA
 VERTICAL PORT 1 531.707 SQ. IN. 24 1 18772.948
 HORIZONTAL PORT 2 250.446 SQ. IN. 6 1 1504.120
 HORIZONTAL PORT 3 3190.288 SQ. IN. 3 3 9572.864
 HORIZONTAL PORT 4 1491.203 SQ. IN. 3 3 4473.609
 8" DIA. PORTS 5 31.895 SQ. IN. 8 8 255.160
 6" DIA. PORTS 6 50.248 SQ. IN. 8 8 401.984
 TOTAL PORT AREA OF 18,22.5 SQUARE INCHES
 21.5 CUB. YDS 5 1285.740 SQ. FT. 16 244319.840 SQ. IN.

TPX.COR.OUT OUTER

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COPIES OF THIS DRAWING
 TO BE MAINTAINED
 IN THE OFFICE OF THE
 PROJECT ENGINEER

ELEVATION THROUGH
CENTER OF LOWER
VERTICAL PORT

SCALE = 1/16

SECTION B-B
LOWER
VERTICAL PORT

SCALE = 1/16

SECTION C-C
LOWER
VERTICAL PORT

SCALE = 1/16

PLAN VIEW OF
NEUTRAL BEAM PORT

SCALE = 1/16

SIDE VIEW
AUXILIARY PORT

SCALE = 1/16

VIEW H-H
AUXILIARY PORT

SCALE = 1/16

VIEW G-G
REF. DRAWING PPL.HWG.TPX.VVGEOM.SHI
COVERS NOT SHOWN

SCALE = 1/16

ELEVATION THROUGH
NEUTRAL BEAM PORT

SCALE = 1/16

END VIEW OF
NEUTRAL BEAM
BEAMLINE PORT

SCALE = 1/16

END VIEW OF
NEUTRAL BEAM
DIAGNOSTICS PORT

SCALE = 1/16

END VIEW OF
NEUTRAL BEAM
AUXILIARY
DIAGNOSTICS PORT

SCALE = 1/16

PORT DEFINITION DRAWING 2

PRELIMINARY ISSUE
NOT APPROVED FOR CONSTRUCTION

COMPUTER GENERATED DRAWING
NO MANUAL CHANGES PERMITTED

PPL.HWG.TPX.VVGEOM.SHY 3/01/93

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Interface Control Document Attachment

TF Magnet (WBS 13) to Vacuum Vessel (WBS 12) ICD

The following pages contain comments to the July 7, 1995 version of the Interface Control Document. These comments include corrections and data for TBD information pertaining to the July 7 status of interface design. Comments that pertain to recent design changes are being compiled for review and discussion during the next phase of work.

PRELIMINARY

THIS IS A CAD GENERATED DRAWING. DO NOT
MAKE MANUAL REVISIONS OR ALTERATIONS.

B235308 PABCOCK & WILCOX
KANSAS CITY, MISSOURI 64108

DATE	TIME	LOCATION	REMARKS
10/10/70	10:00	10000	10000

TOROIDAL FIELD MAGNET

STRUCTURAL PENETRATIONS

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TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1314-0001
		Rev. B Page 1 of 9

TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Poloidal Field Magnet System (WBS 14)**

TPX-ICDP-1314-0001 REVISION B

Date: 7 July 1995

Prepared By:
B. R. Smith
Babcock & Wilcox Company

Concurred By: _____
C. M. Weber, B&W
TF Magnet Project Manager

Concurred By: _____
R. Parman, WEC
PF Magnet Project Manager

Approved By: _____
G. Deis, LLNL
Magnet WBS Manager

Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1314-0001	
		Rev. B	Page 2 of 9

DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First Update based on Feb. 28 Interface Working Meeting at Sunnyvale and telecons between B&W and WEC.	A	1 May 1995
	Second Update based on May TIM and telecons between B&W and WEC.	B	30 June 1995

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1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF) Magnet System (WBS 13) and the Poloidal Field (PF) Magnet System (WBS 14). The PF Magnet System consists of the Central Solenoid (PF 1-4 upper and lower) and Outer PF Coils (PF 5-7 upper and lower) which are mechanically supported by the TF Magnet structure.

This ICD covers the functional, mechanical, and magnetic interfaces between the PF Magnet System and the TF Magnet System. There are no direct fluid or electrical connections between the TF and PF Magnets.

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

- 2.1.1 TPX General Requirements Document
- 2.1.2 TPX Grounding for Equipment and Personnel Safety, 94-940429-PPPL/WRauch-01, dated May 26, 1994
- 2.1.3 Poloidal Field Coil System Current Requirements, 14-941007-MIT-RPillsbury-01, dated October 7, 1994
- 2.1.4 Fault Loads on the PF Coils due to Shorted Terminals during System Dump, 14-940919-MIT-ARadovinsky-01, dated September 19, 1994
- 2.1.5 Worst Fault Load Cases on the Coils of the TPX PF Set due to a Vertical Plasma Disruption Followed by a System Dump with Shorted PF Coils, 14-950327-MIT-ARadovinsky-01, dated March 27, 1994
- 2.1.6 [PPPL/LLNL Drawings--TBD]
- 2.1.7 PF Overview and SRD/Technology Transfer Magnet Meeting: August 9-11, 1994
- 2.1.8 TPX Seismic Design Criteria, 94-941122-PPPL-JSpitzer-01, dated November 22, 1994

2.2 Specifications and Standards

TBD

2.3 Contractor Documents

- 2.3.1 TBD-1: TF and PF Magnet Alignment

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2.3.2 TBD-2: TF and PF Magnet Envelopes

2.3.3 TBD-3: PF-5 Attachments

2.3.4 TBD-4: PF-6 and PF-7 Attachments

2.3.5 TBD-5: Central Solenoid Attachments

2.3.6 TBD Additional Drawings

2.3.7 "TF Interface Design" Presentation, G. Markham/B&W, TPX Magnet System Technical Interchange Meeting #5, May 2-3, 1995

2.3.8 "PF System Vertical Load Distribution (gravity and seismic accelerations)", memo by H. Calvin/WEC, April 13, 1995

2.3.9 "PF/TF Interfaces", memo by M. LaJeunesse/WEC, April 21, 1995

3.0 RESPONSIBILITIES

3.1 TF Magnet Element (WBS 13): Prepare and maintain this document. Design and fabricate the TF Magnet in conformance to the requirements stated herein.

3.2 PF Magnet Element (WBS 14): Design and fabricate the PF Magnet in conformance to the requirements stated herein.

4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. The TF Magnet System shall provide a steady toroidal magnetic field to contain the tokamak plasma.
- b. The PF Magnet System shall provide a variable poloidal magnetic field to accelerate the plasma and to control its position.
- c. The TF Magnet structure shall provide mechanical support and alignment for the PF-5 Upper/Lower, PF-6 Upper/Lower, PF-7 Upper/Lower PF Magnet coils and the Central Solenoid.
- d. The TF and PF magnets shall each withstand plasma disruptions and malfunctions in the other magnet system without sustaining damage.

4.2 Mechanical Interfaces

4.2.1 Envelopes and Attachments

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1314-0001 Rev. B Page 5 of 9
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- a. The TF and PF Magnets shall be nominally located relative to the tokamak alignment datum in accordance with Drawing TBD-1. The objective for TF and PF coil current center alignment accuracy with respect to facility datum shall be 0.010 inches.
- b. The maximum envelopes of the TF and PF Magnets shall be as shown on Drawing TBD-2. The indicated envelopes shall include allowances for manufacturing and alignment tolerances and operational deformations.
- c. The manufacturing tolerance for the PF coil diameter and roundness shall be 0.25 inches. The manufacturing tolerance for the TF case outer surface shape shall be 0.38 inches. Space for alignment between the PF and TF structures shall be 0.75 inches.
- d. PF-5U and -5L shall be attached to the TF structure at eight locations; one attachment per every other TF coil case as shown in Drawing TBD-3. The interfaces shall be flat machined surfaces on the TF structure with indicated bolt holes and shear pins as shown in Drawing TBD. Provisions for isolation and restraint of the PF coils, coil alignment, and accommodation of differential thermal expansion shall be part of the PF Magnet responsibility.
- e. PF-6U and -6L shall be attached to the TF structure at 16 locations; one attachment per TF coil case as shown in Drawing TBD-4. The interfaces for PF-6U and -6L shall be flat machined surfaces on the TF structure with indicated bolt holes and shear pins as shown in Drawing TBD. Provisions for isolation and restraint of the PF coils, coil alignment, and accommodation of differential thermal expansion shall be part of the PF Magnet responsibility.
- f. PF-7U and 7L shall be attached to the TF structure at 16 locations; one attachment per each TF coil case as shown in Drawing TBD. The interfaces for PF-7U and 7L shall be flat machined surfaces on the TF structure with indicated bolt holes and shear pins as shown in Drawing TBD. Provisions for isolation and restraint of the PF coils, coil alignment, and accommodation of differential thermal expansion shall be part of the PF Magnet responsibility.
- g. The Central Solenoid shall be attached to the TF structure by eight linkages; one linkage per every other TF coil case above the inboard leg as shown in Drawing TBD. The interfaces for the CS shall be at the TBD (size) linkage attach point to TBD (size) lugs on the TF structure as shown in Drawing TBD. The linkages shall be provided as part of the PF Magnet System and the corresponding attachment lugs on the TF structure shall be provided as part of the TF Magnet System. Provisions for electrical isolation of the Central Solenoid shall be provided within the PF Magnet System.

4.2.2 Loads

4.2.2.1 PF Weight Distribution and Seismic Loads (Maximum PF weights based on Reference 2.3.7)

- a. The TF Magnet shall support the weight of the PF coils and associated hardware. The maximum PF Magnet component weights are as follows:

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Central Solenoid:

Coil	Weight (lbs.)
PF1	5826
PF2	4649
PF3	2940
PF4	2940

The weight of the total CS assembly (including leads, joints, coolant line plumbing, and CS structure) is 64,021 lbs. Average weight per CS linkage is 8003 lbs.; for worst case loading, the CS weight is supported by two linkages at 32,011 lbs. per linkage (references 2.3.7 and 2.3.8).

- b. The weight of the outer PF coils and mount hardware is distributed uniformly among the support points. (Increased loads on specific mounts due to leads, joints, etc. are discussed in the next paragraph and table.)

For the outer PF coils and corresponding mount hardware, the maximum weights are as follows (references 2.3.7 and 2.3.8):

Coil	Coil Weight (lbs.)	Mount Weight (lbs.) (total)	Weight per Mount including mount hardware (lbs.)
PF5	8926	3700	1578
PF6	23062	448	1469
PF7	18197	TBD	TBD

- c. Outer PF coil features that cause uneven distribution of weight at the support points include the unsupported superconducting coil leads and joints, and coolant line plumbing. Additional weights at specific mounts due to these features are shown in the following table (reference 2.3.8):

Coil	Mount Location/ Load	Mount Location/ Load	Mount Location/ Load	Mount Location/ Load
PF 5U	TF 15/ 68 lbs	TF 3/ 135 lbs	TF 5/ 23 lbs	TF 7/ 23 lbs
PF 5L	TF 7/ 68 lbs	TF 3/ 135 lbs	TF 5/ 23 lbs	TF 7/ 23 lbs
PF 6U	TF 4/ 263 lbs	TF 6/ 451 lbs		
PF 6L	TF 16/ 263 lbs	TF 14/ 451 lbs		
PF 7U	TF 11/ 358 lbs	TF 9/ 441 lbs		
PF 7L	TF 11/ 243 lbs	TF 13/ 377 lbs		

- d. Seismic loads shall be in accordance with "TPX Seismic Design Criteria" (reference 2.1.8).
- e. A potential contact point due to a seismic event exists between the CS seismic snubbers and the TF structure. The snubbers shall not contact the TF structure at room temperature or at operating temperature as shown in Drawing TBD. The load transmitted to the TF structure during a seismic event shall not exceed 65 kN per snubber interface in the radial direction. The total radial load could act through one snubber (reference 2.3.9).

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4.2.2.2 Assembly and Differential Contraction Displacements and Loads

- a. The PF Magnet System shall contain provisions to limit the differential loading of structurally redundant supports on the TF Magnet during assembly of the PF Magnets. The distribution of support loadings for each outer PF coil, and for the Central Solenoid, shall be TBD.
- b. The PF Magnet System shall contain provisions to limit the loading on the TF Magnet due to differential contraction between maximum and minimum temperatures. The maximum temperature difference between the TF structure and any PF coil during cooldown or warm up shall not exceed 50 K. The maximum loading at the CS and PF 5 support points due to differential contraction shall be TBD.
- c. Maximum displacements at the PF 6 and PF 7 mounts at cooldown to 4 K shall be as shown in the following table (Data TBD pending new case/sliding joint design for PF 6 and 7):

TBD Table for PF 6 and PF 7 support displacements at cooldown

- d. The following table shows the maximum forces and moments at each PF 6 and PF 7 mount for cooldown condition with no current in the coils (Data TBD pending new case/sliding joint design for PF 6 and 7):

TBD Table for PF 6 and PF 7 support forces and moments at cooldown

4.2.2.3 Operational Displacements and Loads at PF Support Points

- a. The vertical loads at the PF Magnet support points due to operation within the tokamak flexibility space shall not exceed the values in MIT memo "Poloidal Field Coil System Current Requirements" (reference 2.1.3).
- b. Maximum displacements at the PF 6 and PF 7 mounts during normal operation shall be as shown in the following table (Data TBD pending new case/sliding joint design for PF 6 and PF 7):

TBD Table for PF 6 and PF 7 support displacements during normal operation

- c. The maximum forces and moments at each of the PF 6 and PF 7 mounts during normal operation shall not exceed the values shown in the following table (Data TBD pending new case/sliding joint design for PF 6 and PF 7):

TBD Table for PF 6 and PF 7 support forces and moments during normal operation

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1314-0001
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- d. The loads at the PF Magnet support points due to quench in any PF coil or quench in any TF coil shall not exceed the values in MIT memo "Fault Loads on the PF Coils due to Shorted Terminals during System Dump" (reference 2.1.4).
- e. Vertical and radial loads at the PF Magnet support points due to plasma disruption shall not exceed the values shown in the following table (references 2.3.9 and 2.1.5).

For worst case scenarios, the PF coil support system shall consist of three support points:

Coil	Force Component	Equil Case	Disrupt	Fault	Force per Mount (MN)
CS	Radial	14	lower	n/a	1.2
	Vertical	14	lower	n/a	1.2
PF 5	Radial	1	n/a	5U	8.1
	Vertical	14	upper	n/a	-2.4
PF 6	Radial	9	upper	n/a	7.5
	Vertical	19	lower	n/a	-2.7
PF 7	Radial	13	lower	7U	2.6
	Vertical	18	upper	n/a	-1.2

4.2.3 Thermal Interfaces

- a. The conductive heat transfer between the TF Magnet and the Central Solenoid shall not exceed 2 Watts in either direction during normal operation.
- b. The conductive heat transfer between the TF Magnet and any of the PF-5, -6 and -7 coils individually shall not exceed TBD.
- c. During a fault condition, system shutdown shall occur; therefore, the heat energy transfer between the TF Magnet and any single PF Magnet shall be negligible.

4.3 Fluid Interfaces

None.

4.4 Electrical Interfaces

4.4.1 Isolation

- a. The TF and PF Magnets shall be electrically isolated and separately grounded in accordance with "TPX Grounding for Equipment and Personnel Safety" (reference 2.1.3). The electrical isolators shall be part of the PF Magnet System.
- b. Leakage current across any isolator shall be TBD.

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5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the PF Magnet and TF Magnet elements, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with LLNL and the TPX Systems Integration element.

TF Magnet to PF Magnet Interface Verification Matrix
(Method: A=Analysis, D=Demonstration, I=Inspection, T=Test)

Requirement	Responsibility	Method
TF Magnet shall provide a steady toroidal magnetic field to contain the tokamak plasma (4.1.a)	WBS 13	A
PF Magnet shall provide a variable poloidal magnetic field to accelerate the plasma and to control its position (4.1.b)	WBS 14	A
TF Magnet structure shall provide mechanical support and alignment for the PF-5 Upper/Lower, PF-6 Upper/Lower, PF-7 Upper/Lower Magnet coils and the Central Solenoid (4.1.c)	WBS 13	I
TF and PF magnets shall each withstand plasma disruptions and malfunctions in the other magnet system without sustaining damage (4.1.d)	WBS 13/14	A
TF and PF Magnets shall be nominally located relative to the tokamak alignment datum in accordance with Drawing TBD-1 (4.2.1.a)	TBD	I
The maximum envelopes of the TF and PF Magnets shall be as shown on Drawing TBD-2 (4.2.1.b)	TBD	A/D
The manufacturing tolerance for the PF coil diameter and roundness shall be 0.25 inches (4.2.1.c)	WBS 14	D
The manufacturing tolerance for the TF case outer surface shape shall be 0.38 inches (4.2.1.c)	WBS 13	D
Space for alignment between the PF and TF structures shall be 0.75 inches (4.2.1.c)	WBS 13/14	A/I
PF 5 interfaces shall be flat machined surfaces on the TF structure with indicated bolt holes and shear pins as shown in Drawing TBD (4.2.1.d)	TBD	D/I
Interfaces for PF-6U and -6L shall be flat machined surfaces on the TF structure with indicated bolt holes and shear pins as shown in Drawing TBD (4.2.1.e)	TBD	D/I
Interfaces for PF-7U and 7L shall be flat machined surfaces on the TF structure with indicated bolt holes and shear pins as shown in Drawing TBD (4.2.1.f)	TBD	D/I
Provisions for isolation and restraint of the PF coils, coil alignment, and accommodation of differential thermal expansion shall be part of the PF Magnet responsibility (4.2.1.f)	WBS 14	A/T
Interfaces for the CS shall be at the TBD (size) linkage attach point to TBD (size) lugs on the TF structure as shown in Drawing TBD (4.2.1.g)	TBD	D/I
Provisions for electrical isolation of the Central Solenoid shall be provided within the PF Magnet System (4.2.1.g)	WBS 14	A/T
TF Magnet shall support the weight of the PF coils and associated hardware (4.2.2.1.a)	WBS 13	A/T
Seismic loads shall be in accordance with "TPX Seismic Design Criteria" (reference 2.1.8) (4.2.2.1.d)	WBS 13/14	A/T
Seismic snubbers shall not contact the TF structure at room temperature or at operating temperature as shown in Drawing TBD (4.2.2.1.e)	WBS 14	A/T
PF Magnet System shall contain provisions to limit the differential loading of structurally redundant supports on the TF Magnet during assembly of the PF Magnets (4.2.2.2.a)	WBS 14	A/T
PF Magnet System shall contain provisions to limit the loading on the TF Magnet due to differential contraction between maximum and minimum temperatures (4.2.2.2.b)	WBS 14	A/T
Loads at the PF Magnet support points due to quench in any PF coil or quench in any TF coil shall not exceed the values in MIT memo "Fault Loads on the PF Coils due to Shorted Terminals during System Dump" (reference 2.1.4) (4.2.2.3.d)	WBS 13/14	A/T

SCALE 0 20 40 (INCHES)
0 .5 1.0 (METERS)

TF SUPPORT STRUCTURE
TPX-E-1302-001 P0
REF. TPX-E-9416102 P0

7-27-94
TPX-E-1300-002 P0
ACAD FILE: shore/1112ppl/7-26-94/nogasn/nogasy?
PRO-C FILE: shore/1112ppl/7-26-94/nogasn/11p/c/s-noin

TF MAGNET CONFIGURATION
TPX-E-1300-003
TF MAGNET STRUCTURE
TPX-E-1301-001

ALL DIMS ARE AT
ORIGIN UNLESS OTHERWISE NOTED

PRELIMINARY ISSUE
NOT APPROVED FOR CONSTRUCTION

REVISIONS: 1 REVISED & REBUILT

NO	REVISION	PART / SUPP. STR. NO.	DESCRIPTION / MATERIAL	SPEC. NO.	DATE
1	1	1	1	1	1
2	2	2	2	2	2
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4	4	4	4	4	4
5	5	5	5	5	5
6	6	6	6	6	6
7	7	7	7	7	7
8	8	8	8	8	8
9	9	9	9	9	9
10	10	10	10	10	10

AAA93-106712-0A

FOR ILLUSTRATION PURPOSES ONLY.
NOT DRAWN TO SCALE.

PRELIMINARY

WEC RESPONSIBILITY
B&W RESPONSIBILITY

PF-5 INTERFACE

TF TO PF 6, UPPER INTERFACE LAYOUT

TF INTERFACE — PF INTERFACE

143.252 ± .325

(94.744)

74.544 ± .325

153.345 ± .325

VIEW A-A

NOTES:

1. NOT DRAWN TO SCALE
2. PF ENVELOPE INCLUDES MANUFACTURING TOLERANCE AND LOCATION TO FACILITY.

PRELIMINARY

BABCOCK & WILCOX, A&MS
FOR REFERENCE ONLY
4/28/95

PF6 Upper to TF Interface

SAMPLE

PF6 Lower to TF Interface

SAMPLE

PF7 Upper/Lower to TF Interface

SAMPLE

NOTES

UNLESS OTHERWISE SPECIFIED.

1. ALL DIMENSIONS ARE IN INCHES.
2. DIMENSIONING AND TOLERANCING PER ANSI Y14.5-1982.
3. SURFACE TEXTURE PER ANSI B46.1-1972.

TPX-D-1420-005 P1
1112ppl/7-25-94/31066811

NO. A100	PART / UNL. STR. NO.	DESCRIPTION / MATERIAL	SPEC. NO.	IN
	DATE: 6 MAR 94	CLASSIFICATION: snub		
	DIA.	FILE NAME: snub		
	APPRO.	THIS DOCUMENT IS THE PROPERTY OF		
	REVISION:	THE UNIVERSITY OF CALIFORNIA		
	DATE:	UNIVERSITY OF CALIFORNIA		
		REPRODUCTION PROHIBITED WITHOUT		
		PERMISSION OF THE MECHANICAL		
		ENGINEERING DEPARTMENT.		
		UNIVERSITY OF CALIFORNIA		
		SEISMIC SNUBBER		
		SCALE: 1:1		
		AAA 93-106681-01		
		SHEET 1 OF 1		

PRELIMINARY

NOTES:

1. DIMENSIONS AT ROOM TEMPERATURE.
2. **- T -** IS A VERTICAL AXIS THROUGH THE CENTER OF THE TOKAMAK DEFINED BY THE INTERSECTION OF TWO VERTICAL PLANES, **- X -** & **- Y -**, ESTABLISHED BY THE BUILDING MONUMENTS.
3. **- D -** IS A VERTICAL PLANE **TBD** DEGREES CCW FROM **- X -** AND ESTABLISHES THE CENTERLINE LOCATION OF EACH CS SEISMIC SNUBBER TO TF MOUNTING INTERFACE.
4. **- H -** IS A HORIZONTAL PLANE THROUGH THE CENTER OF THE TOKAMAK, PERPENDICULAR TO **- T -** AND ESTABLISHED BY THE BUILDING MONUMENTS.

NOT TO SCALE

Interface Sketch:
CS Seismic Snubber to TF Structure

4/26/95

PRELIMINARY

Interface Control Document Attachment

TF Magnet (WBS 13) to PF Magnet (WBS 14) ICD

The following pages contain comments to the July 7, 1995 version of the Interface Control Document. These comments include corrections and data for TBD information pertaining to the July 7 status of interface design. Comments that pertain to recent design changes are being compiled for review and discussion during the next phase of work.

PRELIMINARY

SECTION A - A
2X SCALE

PRELIMINARY

THIS IS A CAD GENERATED DRAWING. DO NOT MAKE MANUAL REVISIONS OR ALTERATIONS.									
PROJECT NO. B235308	DATE 5/22/90								
<table border="1"> <tr> <th>APPROVALS</th> <th>DATE</th> </tr> <tr> <td>T. WYNN</td> <td>5/22/90</td> </tr> <tr> <td>S. WARDEN</td> <td>5/23/90</td> </tr> <tr> <td>T. ANTON</td> <td>5/23/90</td> </tr> </table>		APPROVALS	DATE	T. WYNN	5/22/90	S. WARDEN	5/23/90	T. ANTON	5/23/90
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T. WYNN	5/22/90								
S. WARDEN	5/23/90								
T. ANTON	5/23/90								
<table border="1"> <tr> <th>FILE</th> </tr> <tr> <td>BABCOCK & WILCOX</td> </tr> <tr> <td>LYNCHBURG, VIRGINIA 24505</td> </tr> </table>		FILE	BABCOCK & WILCOX	LYNCHBURG, VIRGINIA 24505					
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LYNCHBURG, VIRGINIA 24505									
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REVISION	DATE	BY							
01	5/23/90	PO							

MAGNET SYSTEM
ENVELOPES

NOTES:

1. REMOVE ALL BURRS, FINISHED PRODUCT SHALL BE FREE FROM FOREIGN MATTER.
2. MATERIAL: 316LN UNLESS OTHERWISE SPECIFIED.
3. MARK PART NUMBER & SERIAL NUMBER PER B&W SPEC. BWS-XXXXX.
4. PF6U LOCATIONS ARE TYPICAL OF PF6L MIRROR ABOUT THE MAGNET SYSTEM CENTERLINE

REVISIONS			
ZONE	REV	DESCRIPTION	DATE
		APPROVED

PRELIMINARY

U.S.-INCH/POUND

UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES	
TOLERANCES OF HOLE NUMBERS = 4.00	
TOLERANCE OF DECIMALS	
1. BREAK ALL SHARP EDGES	
2. DO NOT SCALE THIS DRAWING	
3. DIM. TO ANG 114.84 - 1992	
4. MAX. ALL MACHINED SURFACES	

THIS IS A CAD GENERATED DRAWING, DO NOT MAKE MANUAL REVISIONS OR ALTERATIONS.			
CONTRACT NO.	B235308	BABCOCK & WILCOX	
APPROVALS	DATE	LYNCHBURG, VIRGINIA 24505	
DESIGNED BY	8.14.2004	5-23-95	
CHECKED BY	8.14.2004	5-23-95	
APPROVED BY	8.14.2004	5-23-95	
TITLE		PF6U MOUNTING STRUCTURE	
SIZE	SCALE	DRAWING NO.	REV
CT 31399	C-1332103		P0
SHEET

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1315-0001
		Rev. B Page 1 of 5

TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Cryostat (WBS 15)**

TPX-ICDP-1315-0001 REVISION A

Date: 7 July 1995

Prepared By:
B. R. Smith
Babcock & Wilcox Company

Concurred By: _____
C. M. Weber
TF Magnet Project Manager

Concurred By: _____
L Pittenger/LLNL
Cryostat Project Manager

Approved By: _____
G. Deis, LLNL
Magnet WBS Manager

Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1314-0001	
		Rev. A	Page 2 of 5

DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First Update based on format changes and comments from B. Pedrotti/LLNL.	A	7 July 1995

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1314-0001 Rev. A Page 3 of 5
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1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF) Magnet System (WBS 13) and the Cryostat (WBS 15). The Cryostat houses the TF and Poloidal Field (PF) coils and is evacuated prior to cooling down the superconducting coils to minimize the heat load on the magnets.

This document defines the interfaces between the Cryostat (WBS 15) and the TF Magnet system (WBS 13). The TPX Cryostat is an evacuated vessel that encloses both the inner titanium vacuum vessel and the liquid-helium-cooled cold mass. The Cryostat includes thermal insulation and an inner liquid nitrogen-cooled shield to limit the heat loads on the cold mass.

The TF Magnet Bus and Leads element (WBS 136) includes ducts which connect to and are evacuated by the Cryostat as described in the TF Magnet to Electrical Power System ICD (reference 2.3.4). The sealing surfaces between the bus duct and the cryostat port serve as the separations of the systems. A vacuum feed-through is provided in the Cryostat wall for leads to the TF Local Instrumentation and Control (I&C) (WBS 135) as described in the TF Magnet to Central Instrumentation and Control ICD (reference 2.3.2).

2.0 APPLICABLE DOCUMENTS

The following documents of the issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX PROGRAM DOCUMENTS

2.1.1 TPX Toroidal Field Magnet System Description Document

2.1.2 Cryostat System Description Document, dated TBD

2.1.3 91-930319-PPPL: TPX Conceptual Design Overview (March 29-April 1, 1993)

2.1.4 [PPPL/LLNL Drawings--TBD]

2.2 SPECIFICATIONS AND STANDARDS

TBD

2.3 CONTRACTOR DOCUMENTS

2.3.1 TPX-ICDP-1372-0001: TF Magnet (WBS 13) to Cryogenic Equipment (WBS 72) Interface Control Document

2.3.2 TPX-ICDP-1361-0001: TF Magnet (WBS 13) to Central I&C (WBS 61) Interface Control Document

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2.3.3 TPX-ICDP-1213-0001: TF Magnet (WBS 13) to Vacuum Vessel (WBS 12) Interface Control Document

2.3.4 TPX-ICDP-1342-0001: TF Magnet (WBS 13) to TF Power System (WBS 42) Interface Control Document

3.0 RESPONSIBILITIES

3.1 TF Magnet Element (WBS 133): prepare and maintain this document. Design and fabricate the TF Magnet in conformance with the requirements stated herein.

3.2 TF Bus and Leads Element (WBS 136): design and fabricate bus duct in conformance with the requirements stated herein.

3.3 Cryostat Element (WBS 15): design and fabricate the Cryostat in conformance with the requirements stated herein.

4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. The Cryostat shall provide a hard vacuum and a cold radiant background to minimize heat transfer from the external environment to the superconducting TF and PF Magnets.
- b. The Cryostat shall provide vacuum pumping capacity to evacuate the ducts containing the superconducting TF buses between the Cryostat and the spreading room.
- c. The Cryostat shall transmit a signal to TF Local I&C in the event of increases in internal pressure above threshold levels of 1×10^{-4} torr. The signal format shall be in accordance with the TF Magnet to Central I&C ICD (reference 2.3.2).
- d. Except for the feed-through, bus duct connection, and a loss of vacuum signal, there shall be no direct mechanical, fluid, or electrical connections between the TF Magnet and the Cryostat.

4.2 Mechanical Interfaces

4.2.1 Envelopes

- a. The Cryostat and Magnet envelopes shall be as shown in Figure TBD. These envelopes shall include insulation, manufacturing tolerances, and thermal contraction.

4.2.2 Bus Duct and Feed-throughs

- a. The sealing surfaces between the superconducting bus duct and the Cryostat port shall separate the systems and shall provide a high vacuum seal to the atmosphere.

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1314-0001 Rev. A Page 5 of 5
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- b. The Cryostat ports for vacuum ducts through the TF structure to the TPX Vacuum Vessel shall be in accordance with the TF Magnet to Vacuum Vessel ICD (reference 2.3.3) .

4.2.3 Thermal/Vacuum Interfaces

- a. During any condition where a coil is energized, the cryostat vacuum shall exceed 3×10^{-5} torr.
- b. The total heat load on the TF Magnet from the Cryostat walls shall be less than TBD.
- c. Individual joints shall have a helium leak rate no greater than 1×10^{-7} torr-liters/second. The design goal for the outgassing rate from all TF components shall be less than 1×10^{-3} torr-liters/second.

4.3 Fluid Interfaces

None.

4.4 Electrical Interfaces

4.4.1 Isolation

- a. The TF Magnet system and the Cryostat shall be electrically isolated from each other and separately grounded in accordance with the TPX Grounding Specification (reference 2.1.3).

5.0 INTERFACE VERIFICATION SUMMARY

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the Cryostat and TF Magnet Elements, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with LLNL and the TPX Systems Integration Element.

(TBD matrix for requirements and verification method)

TPX Elevation View

Porthole Roll-out for the TPX Cryostat

TPX

TPX

TF & CS LEAD ROUTING - FIGURE 2.1.2.3-III

TPX

2-12-93

ELEVATION
AT 337.5°

SCALE 0 20 40 (INCHES)
0 .5 1.0 (METERS)

TF LEAD &
DEMOUNTABLE JOINT

OF VV & CRYOSTAT
OFFSET OF 2-723

TF LEAD &
DEMOUNTABLE JOINT

TF LEAD &
DEMOUNTABLE JOINT

Cryostat
TF Bus
Leads

SECT A-A
ROTATED 90°

ACAD

LLL2PPL/2-12-93/CRYOGENICS/FIG2123-3

REV	DATE	BY	CHKD	DESCRIPTION / MATERIAL	TYPE NO	STD
001	2-12-93	POSEY	2-12-93	EXISTING		
002	2-12-93	SLACK	2-12-93	NEW		
003	2-12-93	WPS	2-12-93	NEW		
004	2-12-93	WPS	2-12-93	NEW		
005	2-12-93	WPS	2-12-93	NEW		
006	2-12-93	WPS	2-12-93	NEW		
007	2-12-93	WPS	2-12-93	NEW		
008	2-12-93	WPS	2-12-93	NEW		
009	2-12-93	WPS	2-12-93	NEW		
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099	2-12-93	WPS	2-12-93	NEW		
100	2-12-93	WPS	2-12-93	NEW		

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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Tokamak Support Structure (WBS 16)**

TPX-ICDP-1316-0001 REVISION A

Date: 7 July 1995

Prepared By:
B. R. Smith
Babcock & Wilcox Company

Concurred By: _____
C. M. Weber, B&W
TF Magnet Project Manager

Concurred By: _____
D. Knutson, PPPL
Tokamak Support Structure Project Manager

Approved By: _____
G. Deis, LLNL
Magnet WBS Manager

Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1316-0001	
		Rev. A	Page 2 of 6

DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First Update based on Feb. 28 Interface Working Meeting at Sunnyvale and telecons between B&W, Don Knutson/PPPL and Tom Brown/PPPL.	A	7 July 1995

TPX	INTERFACE CONTROL DOCUMENT	TPX-ICDP-1316-0001
	PRELIMINARY	Rev. A Page 3 of 6

1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF) Magnet System (WBS 13) and the Tokamak Support Structure (WBS 16). The Tokamak Support Structure (TSS) provides support for the TF Magnet System and all systems supported from the TF structure.

The TF assembly is mounted to the Tokamak Support Structure which is attached to the Cryostat base structure. The structural supports for the TF Magnet system are located below the TF Magnets and the system. The top end of the support system, the cold end, terminates with a circular ring and the TF Magnet is supported by this ring.

2.0 APPLICABLE DOCUMENTS

The following documents of the issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

- 2.1.1 TPX Toroidal Field Magnet System Description Document
- 2.1.2 TSS System Description Document, dated March-April 1993
- 2.1.3 TPX Grounding for Equipment and Personnel Safety, 94-940429-PPPL/WRauch-01, dated May 26, 1994
- 2.1.4 TPX Seismic Design Criteria, 94-941122-PPPL/J Spetzer-01, dated Nov. 22, 1994
- 2.1.5 [PPPL/LLNL Drawings--TBD]

2.2 Specifications and Standards

TBD

2.3 Contractor Documents

- 2.3.1 Drawing TBD-1 TF Magnet and TSS Envelopes
- 2.3.2 Drawing TBD-2 TF Magnet Alignment
- 2.3.3 Drawing TBD-3 TF Magnet to TSS Attachment
- 2.3.4 Drawing TBD-4 TF TSS Guide Plates
- 2.3.5 Drawing TBD-5 TF Vertical Restraint (Guide Plate) and Vertical Restraint Bracket (Support Ring)

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2.3.6 "TF Interface Design" Presentation, G. Markham/B&W, TPX Magnet System Technical Interchange Meeting #5, May 2-3, 1995.

3.0 RESPONSIBILITIES

3.2.1 **TF Magnet Element (WBS 133):** prepare and maintain this document. Design and fabricate the TF Magnet in conformance with the requirements stated herein.--

3.2.2 **Tokamak Support Structure Element (WBS 16):** design and fabricate the Tokamak Support Structure in conformance with the requirements stated herein.

4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. The Tokamak Support Structure shall provide support and alignment for the TF Magnet under gravitational loads, seismic loads and electromagnetic loads.
- b. There shall be no direct fluid or electrical interfaces between the TF Magnet and the TSS.

4.2 Mechanical Interfaces

4.2.1 Envelopes and Attachments

- a. The envelopes of the TF Magnet and TSS shall be as shown in Drawing TBD-1.
- b. The TSS shall maintain the relative alignment of the TF Magnet with respect to the tokamak datum as defined in Drawing TBD-2 throughout the temperature range from assembly to operation.
- c. The TF Magnet/TSS interface shall be a local steel bearing plate which is welded onto the bottom of each TF coil case, a vertical support bracket and guide pin on the TF intercoil structure, and a guide plate and vertical restraint on the support ring as shown in Drawing TBD-3.
- d. The TF Magnet Element shall provide 4 recesses of 6-8 inches diameter in the bottom of each TF quadrant to allow for the attachment of bearing plates as shown in Drawing TBD-N. The TF Magnet Element shall provide vertical restraint brackets at two locations on each quadrant to interface with the vertical restraint pins on the TSS as shown in Drawing TBD-5.
- e. The TF Magnet Element shall provide 1 recess of 6-8 inches diameter at the inboard location of each quadrant shown in Drawing TBD-N. This recess allows for the attachment of a bearing plate for the temporary inboard support of the TF quadrant during assembly.
- f. The TSS Element shall provide bearing plates, guide pin assemblies, vertical restraint pin assemblies, bolts and any other hardware required for installation of the bearing plates and pins.

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4.2.2 Loads

4.2.2.1 Weight, Seismic and Disruption Loads

- a. The TSS shall support the weight of the TF Magnet and related hardware under gravity and seismic loads. The TSS shall also support the weight transferred through the TF structure of other items such as PF Magnets and related hardware, Field Error Correction Coils and related hardware, TF Cryogenic Equipment, etc. The weight transferred through the TF Magnet to the TSS shall not exceed the following:

-TF Magnet/structure	=	529,200 lbs.
-PF Magnets(Outer coils/Central Solenoid/assoc. hardware) (Maximum weight estimate based on Reference 2.3.6)	=	184,091 lbs.
-Field Error Correction Coils	=	TBD
-Other items	=	<u>TBD</u>
TOTAL	=	TBD

- b. The distribution of weight among the support points shall be TBD.
- c. The vertical and horizontal components of seismic load shall be in accordance with the TPX Seismic Design Criteria (reference 2.1.4).
- d. The TSS shall support the TF Magnet and related hardware for plasma disruption loads.

4.2.2.2 Differential Contraction Displacements and Loads

- a. The maximum displacement at the bearing plate interfaces due to thermal effects shall be TBD.
- b. The TSS shall contain provisions to limit the loading on the TF Magnet due to differential contraction between maximum and minimum temperatures. The maximum load on the TF Magnet due to differential contraction shall be TBD.

4.2.2.3 Magnetic Loads

- a. Magnetic forces between the TF Magnet and the TSS shall not exceed TBD.

4.2.3 Thermal Interfaces

- a. A high resistance to heat flow shall be provided by the TSS element between the TSS and the TF magnet structure. Heat flow between the TSS with its base at room temperature and the TF Magnet structure at 5 K shall not exceed TBD Watts.

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4.3 Fluid Interfaces

None.

4.4 Electrical Interfaces

4.4.1 Isolation

- a. The TF Magnet and the TSS shall be electrically isolated and shall have separate connections to the tokamak single point ground in accordance with the TPX Grounding Specification (reference 2.1.3).
- b. Electrical isolation shall be provided by the TSS element.
- c. Leakage current across any isolator shall be less than TBD.

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the TSS and TF Magnet elements, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with LLNL and the TPX Systems Integration Subcontractor.

(TBD matrix for requirements and verification method)

PRELIMINARY

NO.	REV.	DATE	BY	CHKD.	APP'D.	DESCRIPTION
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SLPSTUD1.DRW 6-16-95

LAYER INFORMATION	
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4	TEXT
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7	TEXT
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TOKAMAK SUPPORT STRUCTURE
(PRELIMINARY) ... & TEMPORARY SUPPORTS

Interface Control Document Attachment

TF Magnet (WBS 13) to Tokamak Support Structure (WBS 16) ICD

The following pages contain comments to the July 7, 1995 version of the Interface Control Document. These comments include corrections and data for TBD information pertaining to the July 7 status of interface design. Comments that pertain to recent design changes are being compiled for review and discussion during the next phase of work.

FWD>Response to ICD review

Return-Path: <Lawrence.#1#Buzz#r#.Pedrotti@quickmail.llnl.gov>
Received: from popcorn.llnl.gov by interserv.com (4.1/SMI-4.1)
id AA25001; Thu, 10 Aug 95 16:24:15 PDT
Received: from quickmail.llnl.gov by popcorn.llnl.gov (8.6.10/LLNL-2.0)
id QAA03428; Thu, 10 Aug 1995 16:27:52 -0700
Message-Id: <n1404050439.52716@quickmail.llnl.gov>
Date: 10 Aug 1995 16:28:29 -0800
From: "Lawrence (Buzz) Pedrotti" <Lawrence.#1#Buzz#r#.Pedrotti@quickmail.llnl.gov>
Subject: FWD>Response to ICD review
To: "Ron Kunz" <rjkunz@interserv.com>
-Mailer: Mail*Link SMTP-QM 3.0.2

Mail*Link(r) SMTP FWD>Response to ICD review - TF
agnet/Support...

hecky,
lost track of whether I forwarded this message to you.

uzz

Date: 8/8/95 8:08 AM
From: Don Knutson
hecky Smith,

concerning the ICD between the TF Field Magnet System (WBS-13) and the Tokamak Support Structure (WBS-16), TPX-ICDP-1316-0001, I have the following comments:

-) Reference 4.2.1, paragraphs c., d., and e.
Paragraph c. notes that the bearing plate is "welded" into the bottom of the TF coil case.
Paragraphs d. and e. refer to milling recesses in the bottom of the TF quadrant for the attachment of bearing plates.

The bearing plate should have a high finish so that the TF assembly will slide smoothly during thermal excursions and also during assembly of the quadrants. In the design of the support structure I envisioned bolting the bearing plates into recesses machined into the bottom of the TF coil cases at assembly. I am concerned that the bearing plates could be distorted during welding and I would also prefer to avoid a welding operation of that nature during assembly. The machined recesses would exist to support the bearing plate in shear, and drilled and tapped holes

FWD>Response to ICD review

would hold the bearing plate to the TF coil case which would be in compression. I would therefore anticipate that rather small bolts would be required and that the heads of the bolts could be recessed into the bearing plates so as not to protrude beyond the bearing surface (The bolts would be located in the bearing plates beyond the extent of the excursion). It is possible that an insulating material will be installed between the bearing plate and the recess in the TF coil case to act as an electrical break (TBD). The bearing plates and hardware would be provided by WBS-16. WBS-13 would mill the recesses and drill and tap for the hardware.

2) Reference 4.2.3 Thermal Interfaces

The resistance to heat flow would be provided in the design of the support structure. The support structure design would attempt to limit the heat flow between the cryostat base and the bearing plugs in the support ring. The heat flow would be limited primarily by the design of the pier assemblies, including the use of titanium and the installation of LN2 intercepts. The bearing material in the base of the pier assemblies and the electrical break between the adjustment mechanism and the bearing plates installed in the TF coil cases (TBD) would also impede the flow of heat; however, that is not the primary mechanism for controlling the heat flow. To state that a high resistance to heat flow shall be provided by the TSS element between the TSS and the TF magnet structure may be misleading.

Please contact me if you have any questions. Don Knutson, 609-243-3007 or e-mail.

----- RFC822 Header Follows -----
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Received: by pierce.llnl.gov (8.6.10/LLNL-1.18/llnl.gov-03.95)
id HAA00884; Tue, 8 Aug 1995 07:59:37 -0700
Received: from pppl.gov by pierce.llnl.gov (8.6.10/LLNL-1.18/llnl.gov-03.95)
id HAA00875; Tue, 8 Aug 1995 07:59:35 -0700
Received: from [198.35.7.245] (fp11_245.pppl.gov [198.35.7.245]) by pppl.gov
(8.6.12/8.6.10) with SMTP id KAA21061; Tue, 8 Aug 1995 10:59:26 -0400
Message-Id: <199508081459.KAA21061@pppl.gov>
MIME-Version: 1.0
Content-Type: text/plain; charset="us-ascii"
Date: Tue, 8 Aug 1995 11:07:48 -0500
To: rjkunz@interserv.com (Att. Becky Smith)
From: dknutson@pppl.gov (Don Knutson)
Subject: Response to ICD review - TF Magnet/Support Structure

FWD>Response to ICD review

c: buzz@llnl.gov (Buzz Pedrotti), dkungl@pppl.gov (Dan Kungl),
jsinnis@pppl.gov (Jim Sinnis), jfrench@pppl.gov (Jim French)

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1317-0001
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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
TPX Assembly and Installation (WBS 17)**

TPX-ICDP-1317-0001 REVISION A

Date: 7 July 1995

Prepared By:
B. R. Smith
Babcock & Wilcox Company

Concurred By: _____
C. M. Weber
TF Magnet Project Manager

Concurred By : _____
D. Knutson, PPPL
TPX Assembly & Installation Manager

Approved By: _____
G. Deis, LLNL
Magnet WBS Manager

Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1317-0001
		Rev. A Page 2 of 9

DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First update based on Feb. 28 Interface Working Meeting at Sunnyvale, telecons between B&W and D. Knutson and T. Brown of PPPL, and telephone meetings with Chuck Halfast of CBI.	A	7 July 1995

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1317-0001 Rev. A. Page 3 of 9
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1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF) Magnet System element (WBS 13) and the TPX Assembly and Installation element (WBS 17). The TF Magnet System includes the TF Magnet (WBS 133), TF Local I&C (WBS 135), and the TF Bus and Leads (WBS 136). The TPX Assembly and Installation element covers receiving and assembly of the TF Magnet, installation of the Vacuum Vessel (WBS 12) within the TF structure, assembly and alignment of the TF Magnet and Vacuum Vessel on the Tokamak Support Structure (WBS 16), installation of the PF Magnets (WBS 14) and Field Error Correction Coils (WBS 19) supported by the TF structure, installation of the TF Bus and Leads and TF Local I&C, and interconnection of the TF Magnet System with the TF Power System (WBS 42), Central I&C (WBS 61), and Cryogenic Equipment (WBS 72).

This ICD covers the routing and location of TF Magnet components within the TPX facility at PPPL. Details of interfacing hardware are covered in the following ICDs:

TPX-ICDP-1213-0001	TF Magnet System (WBS 13) to Vacuum Vessel (WBS 12) ICD
TPX-ICDP-1314-0001	TF Magnet System (WBS 13) to PF Magnet System (WBS 14) ICD
TPX-ICDP-1315-0001	TF Magnet System (WBS 13) to Cryostat (WBS 15) ICD
TPX-ICDP-1316-0001	TF Magnet System (WBS 13) to Tokamak Support Structure (WBS 16) ICD
TPX-ICDP-1342-0001	TF Magnet System (WBS 13) to Field Error Correction Coils (WBS 19) ICD
TPX-ICDP-1319-0001	TF Magnet System (WBS 13) to TF Power System (WBS 42) ICD
TPX-ICDP-1361-0001	TF Magnet System (WBS 13) to Instrumentation & Control Systems (WBS 61) ICD
TPX-ICDP-1372-0001	TF Magnet System (WBS 13) to Cryogenic Equipment (WBS 72) ICD

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

- 2.1.1 TPX Toroidal Field Magnet System Design Description, dated March 16, 1993
- 2.1.2 TPX Grounding for Equipment and Personnel Safety, 94-940429-PPPL/WRauch-01, dated May 26, 1994
- 2.1.3 TPX Assembly Plan, dated March 1994
- 2.1.4 [PPPL/LLNL Drawings -- TBD]

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1317-0001
		Rev. A Page 4 of 9

2.2 Specifications and Standards

TBD

2.3 Contractor Documents

2.3.1 TPX-ICDP-1213-0001: TF Magnet System (WBS 13) to Vacuum Vessel (WBS 12) ICD

2.3.2 TPX-ICDP-1314-0001: TF Magnet System (WBS 13) to PF Magnet System (WBS 14) ICD

2.3.3 TPX-ICDP-1315-0001: TF Magnet System (WBS 13) to Cryostat (WBS 15) ICD

2.3.4 TPX-ICDP-1316-0001: TF Magnet System (WBS 13) to Tokamak Support Structure (WBS 16) ICD

2.3.5 TPX-ICDP-1342-0001: TF Magnet System (WBS 13) to Field Error Correction Coils (WBS 19) ICD

2.3.6 TPX-ICDP-1319-0001: TF Magnet System (WBS 13) to TF Power System (WBS 42) ICD

2.3.7 TPX-ICDP-1361-0001: TF Magnet System (WBS 13) to Instrumentation & Control Systems (WBS 61) ICD

2.3.8 TPX-ICDP-1372-0001: TF Magnet System (WBS 13) to Cryogenic Equipment (WBS 72) ICD

2.3.9 TBD Drawings

2.3.10 TPX-ICDS-133-136-01: TF Magnet to TF Bus and Leads ICD

2.3.11 TPX-ICDS-133-135-01: TF Magnet to TF Local I&C ICD

3.0 RESPONSIBILITIES

3.1 TF Magnet Element (WBS 133): Prepare and maintain this document. Design, fabricate, verify, and deliver the TF Magnet in conformance to the requirements stated herein.

3.2 TF Bus and Power Leads Element (WBS 136): Design, fabricate, verify, and deliver the TF Bus and Power Leads in conformance to the requirements stated herein.

3.3 PPPL/TPX Systems Integration Element (WBS 94): Provide interface requirements derived from system-level analysis and planning in the areas of alignment, scheduling etc. Verify performance of the integrated tokamak, including the TF Magnet System.

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3.4 TPX Assembly and Installation Element (WBS 17): The Assembly and Installation element (WBS 17) covers receiving and assembly of the TF Magnet quadrants; installation of the Vacuum Vessel (WBS 12) within the TF structure; assembly and alignment of the TE Magnet and Vacuum Vessel on the Tokamak Support Structure (WBS 16); installation of the PF Magnets (WBS 14) and Field Error Correction Coils (WBS 19) supported by the TF Structure; and installation of the TF Bus and Leads and TF Local I&C, and interconnection of the TF Magnet System with the TF Power System (WBS 42), Central I&C (WBS 61), and Cryogenic Equipment (WBS 72).

4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. The deliveries of TF Magnet System components, and the sequence of assembly, shall be in accordance with Figure 4.1-1.
- b. The TF Magnet System shall be installed within the TPX complex at PPPL, as shown on the TPX Site Plan, Figure 4.1-2.
- c. The TPX Assembly and Installation element shall provide labor, fixtures, tools, and material to assemble the TF Magnet System at the Princeton Plasma Physics Laboratory, and to connect the Magnet System to interfacing systems.
- d. The TPX Magnet quadrants and Vacuum Vessel segments shall be pre-assembled in the Mockup Area, and transported to the test cell for final assembly as shown in Figure 4.1-3.

4.2 Mechanical Interfaces

4.2.1 TF Quadrant Pre-Assembly

- a. The TF Magnet shall be received as TBD (octants or quadrants) for pre-assembly in the Mockup Area. TBD fixtures as shown in Figure TBD shall be provided by the TF Magnet element for handling the modules. The weight of the TF quadrant and fixture shall not exceed TBD.
- b. The Vacuum Vessel segments shall be installed in the bore of the TF quadrant at an assembly station in the Mockup Area. The Vacuum Vessel quadrants shall be inserted into the TF quadrant using the fixture and corresponding track system shown in Drawings 4.2-1, 4.2-2, 4.2-3 and 4.2-4. This fixture and track system shall be provided by the Assembly and Installation element. The fixture and track system shall weigh no more than TBD and shall contain provisions to prevent surface damage to the TF structure.
- c. The fixture shall maintain positive control of the Vacuum Vessel position to prevent interference between the Vacuum Vessel segment and the bore of the TF quadrant. The relative dimensions of the Vacuum Vessel and the TF Magnet shall be in accordance with the TF Magnet System to Vacuum Vessel ICD (reference 2.3.1).

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- d. After the Vacuum Vessel is rotated into the bore of the TF quadrant, it shall be temporarily supported by the TF structure at the top vacuum port with TBD fixture as shown in Drawing TBD. The maximum weight of a Vacuum Vessel segment (excluding internal components, horizontal and vertical ports, and borated water) to be supported by the TF structure shall be no greater than TBD.
- e. Clearance shall be provided in the TF structure for installing and welding divertor pumpout stubs and other components that extend through the TF quadrant and attach to the Vacuum Vessel, in accordance with Drawing TBD.
- f. The Field Error Correction Coils shall be attached in TBD sequence to the TF quadrant structure as shown in Drawing TBD. Mounting pads and handling fixtures shall be provided by the Field Error Correction Coil element in accordance with the TF Magnet System to Field Error Correction Coil ICD (reference 2.3.5).
- g. A transporter as shown in Drawing TBD shall be provided by Assembly and Installation element to deliver the completed TF quadrant to the test cell. The transporter shall attach to the TF quadrant at locations shown on Drawing TBD.

4.2.2 TF Quadrant Placement on Tokamak Support Structure

- a. TF quadrants shall be placed in the test cell as shown in Figure TBD using an overhead crane and a lifting fixture equipped with a precision load positioner provided by the Assembly and Installation element. The interface between the lifting fixture and the TF Magnet shall be as shown on Drawing TBD. The weight of a TF quadrant with Vacuum Vessel segment and Field Error Correction Coils installed shall not exceed the upgraded crane capacity.
- b. Each TF quadrant shall be located on the Tokamak Support Structure and temporary supports as shown in Drawing TBD. The interfaces between the Tokamak Support Structure and temporary supports shall be in accordance with the TF Magnet System to Tokamak Support Structure ICD (reference 2.3.4). Temporary supports shall be provided by the Assembly and Installation element.

4.2.3 TF Quadrant Final Alignment and Bolting

- a. Final alignment of the TF quadrants, when all four of the quadrants are positioned on the Support Structure, shall be in accordance with Drawing TBD.
- b. The TF quadrants shall be moved radially into position using jacks temporarily mounted on the support ring as shown in Drawing TBD. Jacks shall also be used to temporarily support TF joints during assembly. The jacks shall be provided by the Assembly and Installation element.
- c. A fixture and instrumentation in the bore of the machine shall be provided by the Assembly and Installation element to verify the locations of the TF windings, in accordance with Drawing

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1317-0001 Rev. A Page 7 of 9
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TBD. Fiducials indicating the coil locations shall be provided on the TF cases by the TF Magnet element in accordance with Drawing TBD.

- d. The Vacuum Vessel weight shall be unloaded from the TF structure by TBD temporary or permanent supports during alignment of the TF Magnet as shown in Drawing TBD. Temporary and permanent supports shall be provided by the Assembly and Installation element. The TF Magnet shall be aligned with respect to the tokamak datum. The Vacuum Vessel shall be aligned with respect to the TF Magnet.
- e. Bolting of the TF quadrants shall be in accordance with Procedure TBD provided by the TF Magnet element.
- f. Clearance shall be provided in the TF structure for alignment and welding of the Vacuum Vessel segments in accordance with Drawing TBD.
- g. The Assembly and Installation element shall provide work platforms for access to all final assembly operations, including fluid and electrical connections. Attachment of work platforms on the TF structure shall be TBD.

4.2.4 PF Coil and Central Solenoid Assembly

- a. Upon completion of TF quadrant bolting, Poloidal Field (PF) coils PF-5, PF-6, and PF-7 shall be attached to the TF structure as shown on Drawing TBD. Mounting brackets and procedures shall be provided by the PF Magnet element. Lifting fixtures shall be provided by the Assembly and Installation element.
- b. The PF Central Solenoid shall be lowered into the bore of the machine by a lifting apparatus with a precision load positioner provided by the Assembly and Installation element. Hardware to attach the Central Solenoid to the TF Magnet shall be provided by the PF Magnet element.
- c. The TF Magnet shall provide access for installation and alignment of the PF Magnets in accordance with Drawing TBD.

4.2.5 TF Local I&C Installation

- a. TF Signal Conditioning and Isolation System electronics shall be installed next to the instrumentation lead penetration through the Cryostat, as shown on Drawing TBD.
- b. Cables connecting the TF Magnet, Signal Conditioning and Isolation System, TF Local I&C in the TPX Control Room, and other systems shall be routed as shown on Drawing TBD. The electronic assemblies and cables shall be provided by the TF Local I&C element.
- c. Routing and installation of instrumentation leads on the TF Magnet structure shall be as shown on Drawing TBD. Magnet instrumentation and leads to the Cryostat vacuum feed-through shall be provided by the TF Magnet element.

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- d. Instrumentation lead feed-throughs on the Cryostat shall be installed in accordance with the TF Magnet to Cryostat ICD (reference 2.3.3). The vacuum feed-through connectors shall be provided by the TF Local I&C element.
- e. Routing and installation of instrumentation leads from the TF Bus and Leads shall be in accordance with Drawing TBD. Bus instrumentation and leads to vacuum feed-through connectors on the current lead vacuum boxes shall be provided by the TF Bus and Leads element. The vacuum feed-throughs and external cables shall be provided by the TF Local I&C element.

4.2.6 TF Bus and Leads Installation

- a. The TF Bus and Leads shall be routed from the test cell to the spreading room in accordance with Drawing TBD.
- b. Inter-coil splices and coil-to-bus splices on the magnet shall be in accordance with the TF Magnet to TF Bus and Leads ICD (reference 2.3.10) and procedure TBD. Splice blocks shall be provided by the TF Magnet element.
- c. Bus segment connections shall be made in accordance with Drawing TBD and Procedure TBD. Demountable joints shall be provided by the TF Bus and Leads element.

4.3 Fluid Interfaces

- a. Coolant lines to the TF Magnet shall be installed in accordance with Drawing TBD and Procedure TBD. Voltage isolators and flow, pressure, and temperature sensors shall be provided by the TF Magnet element for installation in the cryogenic lines in the vicinity of the magnet lead boxes.
- b. Coolant lines to the TF Bus and Leads shall be installed in accordance with Drawing TBD and Procedure TBD. Voltage isolators and flow, pressure, and temperature sensors shall be provided by the TF Bus and Leads element for installation in the cryogenic lines at the bus supplies and returns in the lead vacuum boxes.

4.4 Electrical Interfaces

- a. Connections between the TF Magnet, TF Local I&C, and Central I&C shall be in accordance with Drawing TBD. Connections shall be in accordance with the TF Magnet Local I&C Wiring Diagram, Drawing TBD.
- b. Connections between the TF Magnet coils and TF Bus shall be in accordance with Drawing TBD and the TF Power Wiring Diagram, Drawing TBD.
- c. Connections between the TF Magnet Bus and Leads and the TF Power System shall be in accordance with Drawing TBD.

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- d. Grounding of TF Magnet System components shall be in accordance with TPX Grounding for Equipment and Personnel Safety (reference 2.1.2).

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware and software designs meet the interface requirements specified herein rests with the TF Magnet element, TF Local I&C element, TF Bus and Leads-element, and TPX Assembly and Installation element, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with PPPL and the TPX Systems Integration element.

Interface Verification Responsibility and Method Matrix

TPX ASSEMBLY PLAN

FIG. 4.1-1

TPX ASSEMBLY PLAN

N CH 1994
REV. 3-21-9.
Sheet 2 of 5

TPX ASSEMBLY PLAN

WEEKS

35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
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Fig 4.1-1-cont.

35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
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TPX ASSEMBLY PLAN

WEEKS

55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
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Fig A.1-1 cont.

55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
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TPX ASSEMBLY PLAN

WEEKS

75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
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FIRST PLASMA

INTEGRATED SYSTEMS TESTS

15

64

REINSTALL SHIELD BLOCKS
IN TEST CELL DOORS

62

PREP. FOR TESTS
INST'L SHIELD
PLUGS

63

2

Fig 4.1-1 cont.

75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
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TEST CELL & MOCKUP BUILDING AREA LAYOUT
Fig. 4.1-3

PRELIMINARY

DRAWING 4.2-1

APR 18 1995

STUDY ONLY
PICMA7X.DRW

PRELIMINARY

DRAWING 4.2-2

PRELIMINARY

DRAWING 4.2-3

APR 18 1995

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PRELIMINARY

DRAWING 4.2-4

TF Quadrant Assembly

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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Field Error Correction Coils (WBS 19)**

TPX-ICDP-1319-0001 REVISION A

Date: 7 July 1995

Prepared By:
B. R. Smith
Babcock & Wilcox Company

Concurred By: _____
C. M. Weber, B&W
TF Magnet Project Manager

Concurred By : _____
B. Ellis, PPPL
Field Error Correction Coils Manager

Approved By: _____
G. Deis, LLNL
Magnet WBS Manager

Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager

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DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	--	4 Jan 1995
	First update based on format changes and telecons with B. Ellis/PPPL.	A	7 July 1995

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1319-0001 Rev. A Page 3 of 5
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1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF) Magnet System (WBS 13) and the Field Error Correction (FEC) Coils (WBS 19). The FEC Coils are provided to compensate the non-axisymmetric error components in the magnetic field.

The FEC Coil system consists of twelve "window frame" shaped coils with three coils provided on each TF Magnet quadrant: one above, one below and one mounted on the outer periphery. The TF Magnet structure mechanically supports and aligns the FEC Coils.

2.0 APPLICABLE DOCUMENTS

The following documents of the issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

- 2.1.1 TPX Toroidal Field Magnet System Description Document
- 2.1.2 Field Error Correction Coil System Description Document
- 2.1.3 91-930319-PPPL: TPX Conceptual Design Overview (March 29-April 1, 1993)
- 2.1.4 [PPPL/LLNL Drawings--TBD]
- 2.1.5 94-902429-PPPL/WRauch-01, TPX Grounding Specification

2.2 Specifications and Standards

TBD

2.3 Contractor Documents

TBD

3.0 RESPONSIBILITIES

3.1 TF Magnet Element (WBS 133): prepare and maintain this document. Design and fabricate the TF Magnet in conformance with the requirements stated herein.

3.2 Field Error Correction Coil Element (WBS 19): design and fabricate the FEC Coils in conformance with the requirements stated herein.

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4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. The FEC Coils are provided to compensate the non-axisymmetric error components in the magnetic field.
- b. The TF Magnet structure mechanically supports and aligns the FEC Coils.
- c. There are no direct fluid or electrical connections between the TF Magnet and the Field Error Correction Coils.

4.2 Mechanical Interfaces

4.2.1 Envelopes

- a. Three FEC Coils shall be located on each TF Magnet quadrant as shown in Drawing TBD.
- b. The FEC Coils shall accommodate any movement of the TF structure during cool-down and normal operation.
- c. The TF Magnet element shall provide mounting surfaces with TBD bolt holes as shown in Drawing TBD. FEC Coil attachment fixtures shall be provided by the FEC Coil element. The attachment fixtures shall provide thermal and electrical isolation between the FEC Coils and the TF structure. The attachment fixtures shall be TBD size and shall be located at TBD on the TF structure as shown in Drawing TBD.
- d. Leads to the FEC Coils shall be supported by the TF structure as shown in Drawing TBD.

4.2.2 Loads

4.2.2.1 Weights

- a. The weight of a single top or bottom FEC Coil shall not exceed TBD. The weight of a single outer periphery FEC Coil shall not exceed TBD. The weight of the entire FEC Coil system including mounting pads and leads shall not exceed TBD.

4.2.2.2 Electromagnetic Loads

- a. The electromagnetic loads in TBD direction between the FEC Coils and the TF Magnet shall be no greater than TBD. These loads shall be reacted through the FEC Coil mounting pads.

4.2.3 Thermal Interfaces

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- a. The FEC Coils shall accommodate differential contraction of the TF structure between temperature extremes. FEC Coil mounting point displacement shall be less than TBD at the temperature extremes.
- b. The maximum heat load to the TF Magnet from the FEC Coils shall be 1 Watt per FEC Coil transferred into the 4 K TF surfaces.

4.3 Fluid Interfaces

None.

4.4 Electrical Interfaces

4.4.1 Isolation

- a. The FEC Coils shall be electrically isolated from the TF Magnet and separately grounded in accordance with TPX Grounding Specification, reference 2.1.5.

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the FEC Coil and TF Magnet Elements, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with LLNL and the TPX Systems Integration Element.

(TBD matrix for requirements and verification method)

Figure 4-4 TF Quadrant Assembly

PLAN - UPPER AND OUTER COILS
(rotated 47.25°)

SCALE 0 20 40 (INCHES)
0 .5 1.0 (METERS)

PLAN - LOWER COIL
(rotated 47.25°)

SCALE 0 20 40 (INCHES)
0 .5 1.0 (METERS)

COMPUTER GENERATED DRAWING
NO MANUAL CHANGES PERMITTED

TPX,RLG,FECC,QUAD,PLAN

NO.	REV.	DATE	BY	CHKD.	DESCRIPTION	APPROVED BY	REVISIONS
1					PRINCETON PLASMA PHYSICS LABORATORY PRINCETON UNIVERSITY TOKAMAK PHYSICS EXPERIMENT PRELIMINARY DESIGN 2.25M BASELINE 4.00 TESLA CONFIGURATION		
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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Vacuum Pumping Systems (WBS 34)**

TPX-ICDP-1334-0001 (First Release)

Date: 7 July 1995

Prepared By:
B. R. Smith
Babcock & Wilcox Company

Concurred By: _____
C. M. Weber
TF Magnet Project Manager

Concurred By: _____
TBD
Vacuum Pumping Systems Project Manager

Approved By: _____
G. Deis, LLNL
Magnet WBS Manager

Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1334-0001
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DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	7 July 1995

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1.0 SCOPE

This document provides a detailed description of the Toroidal Field (TF) Magnet System (WBS 13) to Vacuum Pumping Systems (WBS 34) Interfaces for the TPX. The Vacuum Pumping Systems consist of pumping ducts that are attached to vertical ports on the bottom of the vacuum vessel assembly and extend through the bottom of the TF structure, and vertical supports that attach the vessel assembly to the cryostat structure.

There are no direct fluid or electrical interfaces between the Vacuum Pumping Systems and the TF Magnet. Mechanical interfaces during tokamak assembly are defined in the TF Magnet to Tokamak Assembly and Installation ICD (reference 2.3.1).

2.0 APPLICABLE DOCUMENTS

The following documents of the issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

2.1.1 TPX General Description Document

2.1.2 TPX Grounding for Equipment and Personnel Safety, 94-9440429-PPPL/WRauch-01, dated May 26, 1994

2.1.3 [PPPL/LLNL Drawings--TBD]

2.2 Specifications and Standards

TBD

2.3 Contractor Documents

2.3.1 TPX-ICDP-1317-0001: TF Magnet (WBS 13) to Tokamak Assembly and Installation (WBS 17) Interface Control Document

3.0 RESPONSIBILITIES

3.1 TF Magnet Element (WBS 13): prepare and maintain this document. Design and fabricate the TF Magnet in conformance with the requirements stated herein.

3.2 Vacuum Pumping Systems Element (WBS 34): design and fabricate the Vacuum Pumping Systems in conformance with the requirements stated herein.

4.0 REQUIREMENTS

4.1 Functional Interfaces

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- a. The TF Magnet shall provide access for the Vacuum Pumping System through the TF structure.
- b. The Vacuum Pumping Systems shall provide TBD vacuum inside the vacuum vessel to ensure the purity of the tokamak plasma.

4.2 Mechanical Interfaces

4.2.1 Envelopes

- a. The TF Magnet structure shall contain penetrations to clear the vacuum pumpout ports as shown in Drawing TBD.
- b. The envelopes of Vacuum Pumping System ports shall include allowances for assembly and alignment tolerances and differential thermal contraction. The port envelopes shall be as shown in Drawing TBD.

4.2.2 Loads

4.2.2.1 Assembly and Differential Contraction Displacements and Loads

The differential thermal expansion and contraction of the Vacuum Pumping System ducts between maximum and minimum temperatures shall not exceed TBD.

4.2.2.2 Seismic Displacements and Loads

TBD

4.2.2.3 Operational Displacements and Loads

TBD

4.2.3 Thermal Interface

- a. The maximum temperature of the Vacuum Pumping System ducts shall not exceed TBD during normal operation.
- b. The Vacuum Vessel Pumping System ports shall be covered with super insulation to limit the total radiation heat loss to the TF Magnet to TBD.

4.3 Fluid Interfaces

None.

4.4 Electrical Interfaces

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4.4.1 Isolation

- a. The TF Magnet system and the Vacuum Pumping Systems shall be electrically isolated from each other and separately grounded in accordance with the TPX Grounding Specification (reference 2.1.2).

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the Vacuum Vessel and TF Magnet Elements, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with LLNL and the TPX Systems Integration Element.

(TBD matrix for requirements and verification method)

Interface Control Document Attachment

TF Magnet (WBS 13) to Vacuum Pumping Systems (WBS 34) ICD

The following pages contain comments to the July 7, 1995 version of the Interface Control Document. These comments include corrections and data for TBD information pertaining to the July 7 status of interface design. Comments that pertain to recent design changes are being compiled for review and discussion during the next phase of work.

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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Electrical Power System (WBS 42)**

TPX-ICDP-1342-0001

Date: 7 July 1995

**Prepared By:
B. R. Smith
Babcock & Wilcox Company**

**Concurred By: _____
C. M. Weber
TF Magnet Project Manager**

**Concurred By: _____
C. Neumeyer, PPPL
Electrical Power System WBS Manager**

**Approved By: _____
G. Deis, LLNL
Magnet WBS Manager**

**Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager**

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DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First Update based on comments from C. Neumeier/ PPPL and ICD format changes.	A	7 July 1995

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1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF)-Magnet System (WBS 13) and the TF Power System (WBS 42). The TF Power System supplies direct current to energize the TF Magnet coils, and contains switchgear and components to dissipate the energy in the coils in the event of a quench or other abnormal condition.

The TF Magnet System includes the TF Magnet element (WBS 133) and the TF Bus and Power Leads element (WBS 136). The TF Magnet is delivered as two-coil octants or quadrants which are assembled at PPPL. Leads from the magnet coils are spliced to interconnect eight coils in series with each of two TF Buses, using procedures and components (electrical isolators and cooled splice blocks) supplied under the TF Magnet element. The superconducting (NbTi) buses from the magnet to the power supply penetrate the cryostat and are routed to the spreading room in the power supply building. The TF Buses terminate in vacuum dewars that each contain a superconductor-to-copper transition and gas-cooled leads that make the transition from the 5 K operating temperature of the bus to room temperature (300 K).

The interconnections on the magnet, installation of the buses, and connections from the gas-cooled leads to room-temperature buses in the spreading room, are made under the TPX Assembly and Installation element (WBS 17), and are covered in the TF Magnet System to Tokamak Assembly and Installation ICD (reference 2.3.3). The TF Magnet leads and TF Bus interfaces with Cryogenic Equipment fluid line connections in the eight magnet lead boxes ("chimneys"), at bus inlets within the cryostat, and at return lines in the lead vacuum boxes in the spreading room, are covered in the TF Magnet to Cryogenic Equipment ICD (reference 2.3.2). Bus penetrations of the cryostat are covered in the TF Magnet System to Cryostat ICD (reference 2.3.1).

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

- 2.1.1 TPX Toroidal Field Magnet System Design Description, dated March 16, 1993
- 2.1.2 TF Power System Design Description, dated September 29, 1994
- 2.1.3 TPX Grounding for Equipment and Personnel Safety, 94-940429-PPPL/WRauch-01, dated May 26, 1994
- 2.1.4 [PPPL/LLNL Drawings – TBD]

2.2 Specifications and Standards

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2.3 Contractor Documents

- 2.3.1 TPX-ICDP-1315-0001: TF Magnet System (WBS 13) to Cryostat (WBS 15) Interface Control Document
- 2.3.2 TPX-ICDP-1372-0001: TF Magnet System (WBS 13) to Cryogenic Equipment (WBS 72) Interface Control Document.
- 2.3.3 TPX-ICDP-1317-0001: TF Magnet System (WBS 13) to Tokamak Assembly and Installation (WBS 17) Interface Control Document.
- 2.3.4 T3B-10043 TF Hemisphere Charging Circuit
- 2.3.5 TPX-ICDS-133-136-0001: TF Magnet (WBS 133) to TF Bus and Leads (WBS 136) Interface Control Document

3.0 RESPONSIBILITIES

- 3.1 TF Magnet Element (WBS 133): Prepare and maintain this document. Design, fabricate, and verify the TF Magnet in conformance to the requirements stated herein.
- 3.2 TF Bus and Power Leads Element (WBS 136): Design, fabricate, and verify the TF Bus and Power Leads in conformance to the requirements stated herein.
- 3.3 TF Magnet Power System Element (WBS 42): Procure and integrate the power supply and magnet protection equipment, and design and fabricate associated room-temperature buses in conformance to the requirements stated herein.

4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. The TF Power System shall supply direct current to energize the TF Magnet during normal operation as specified herein. Eight TF coils shall be connected in series with each of two parallel sets of buses and leads.
- b. The TF Power System shall include switchgear and dump resistors capable of safely dissipating the energy in the TF Magnet in response to a signal from TF Magnet Local Instrumentation and Control.
- c. Other than electrical power connections in the spreading room, there shall be no mechanical or fluid interfaces between the TF Power System and the TF Magnet System.

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4.2 Mechanical Interfaces

- a. The TF Magnet coils shall be connected to the TF Magnet Bus as shown in LLNL drawing AAA94-100605-00. The electrical connections are TBD [locations, splice block configuration, etc.].
- b. The routing and attachments of the TF bus on the TF Magnet structure, and the routing of the TF Bus from the tokamak to the spreading room are defined in the TF Magnet System to TF Bus and Leads ICD (reference 2.3.5).
- c. The TF Bus shall interface with the room-temperature bus from the TF Power System at lead vacuum boxes in the spreading room, as shown in Figure TBD. The transition shall allow for bus contraction not to exceed 11 in. from room temperature to operating temperature. Details of the room-temperature bus connection are TBD (material, size, bolt pattern, surface preparation, allowable resistance, etc.).

4.3 Fluid Interfaces

None.

4.4 Electrical Interfaces

4.4.1 Normal Operation

- a. The maximum DC current supplied to each TF Bus shall be 33.5 kA. Ripple or spurious signals on the DC current shall not exceed TBD.
- b. The inductance of each TF coil circuit measured at the interface terminal shall be TBD Henrys and resistance shall be TBD Ohms.
- c. The rate of change of current shall not exceed 3.35 kA per min, charging or discharging.
- d. The TF Magnet current shall be constant within +/- TBD% between plasma initiation and discharge.

4.4.2 Coil Protection

- a. The TF Power System shall be capable of discharging the TF Magnet energy of TBD MJ in a "fast dump" or a "slow dump", in response to signals from the TF Local I&C. The signal format shall be TBD.
- b. In a "fast dump", the coil protection system shall discharge the magnet at a maximum voltage of 15 kV. The TF Power System switchgear shall initiate dump within TBD s of receiving a "fast dump" signal. The time constant of the dump circuit shall not exceed 5 s.

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- c. In a "slow dump", the coil protection system shall discharge the TF Magnet at a voltage of 7.5 kV.
- d. The magnet protection system shall be fail safe, such that if the interface from TF Local I&C to the TF Power System is broken, or if local power is lost at the TF Local I&C, then a fast dump shall be initiated in the TF Power System.

4.4.3 Grounding

- a. The TF Magnet and TF Power systems shall be separately grounded in accordance with TPX Grounding for Equipment and Personnel Safety, reference 2.1.3.

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the TF Magnet element, TF Bus element, and TF Power System element, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with PPPL and the TPX Systems Integration Subcontractor.

(TBD matrix for requirements vs. verification method and responsibility)

Figure 1-1 TF Magnet & Power Systems Block Diagram

1.1 System Design Description (REF. 1.2)

As shown on Figure TF-1.1-1 the TF circuit consists of two interleaves of coils and two interleaves of power supply equipment, both of which contain DC circuit breakers (DCCBs) and dump resistors for quench protection, and one of which contains the TF converter. A more detailed representation is given on TPX-D-4201 sheet 1.

Figure TF-1.1-1: TF Circuit Schematic

TF & CS LEAD ROUTING - FIGURE 2.1.2.3-III

TPX

2-12-93

TF LEAD & DEMOUNTABLE JOINT

SECTION A-A
ROTATED 90°

LLL2PPL/2-12-93/CRYDGENICS/FIG2123-3

NO.	REV.	DATE	BY	CHKD.	APP.	DESCRIPTION
1						ISSUED FOR CONSTRUCTION
2						ISSUED FOR CONSTRUCTION
3						ISSUED FOR CONSTRUCTION
4						ISSUED FOR CONSTRUCTION
5						ISSUED FOR CONSTRUCTION
6						ISSUED FOR CONSTRUCTION
7						ISSUED FOR CONSTRUCTION
8						ISSUED FOR CONSTRUCTION
9						ISSUED FOR CONSTRUCTION
10						ISSUED FOR CONSTRUCTION

NOTES

UNLESS OTHERWISE SPECIFIED

1. ALL DIMENSIONS ARE IN INCHES
2. DIMENSIONS AND TOLERANCES .
ANSI Y14.5M-1982.
3. SURFACE TEXTURE PER ANSI B46.1-1988

TPX-E-1304-008 P0

shore/III2ppl/7-25-94/41006051

[illegible]

FIGURE 2.1.3.1-I

CLAMPING BOLTS W/CAPTURED NUTS OR THREADS FOR EASY REMOTE REMOVAL

Ø.50" JUMPER (COULD BE CLOSER TO BUSS TO FIT IN PIPE)

This isometric diagram shows a long, rectangular busbar with a series of circular holes along its length. A curved jumper is attached to the bottom of the busbar. Two clamping bolts are shown securing the busbar to a surface. Section lines A-A are indicated at both ends of the assembly.

BOTH HALVES THE SAME

SECTION A-A

A
C
L
C

. LLL2PPL/2-12-93/CRYOGENICS/FIG2131-1

[illegible]

TF cryogenic bus to
gas-cooled lead interface

**Interface Control Document
Attachment**

TF Magnet (WBS 13) to Electrical Power System (WBS 42) ICD

The following pages contain comments to the July 7, 1995 version of the Interface Control Document. These comments include corrections and data for TBD information pertaining to the July 7 status of interface design. Comments that pertain to recent design changes are being compiled for review and discussion during the next phase of work.

TO: L. R. PEDROTTI
FROM: C NEUMEYER
SUBJECT: COMMENTS ON TF PRELIMINARY ICD

Keywords: TF Coils, TF Power System, Grounding

References:

- (1) 47-950524-PPPL-CN-01, "Power Supply Fault Modes and Responses"
- (2) 47-950731-PPPL-CNeumeyer-01, "Review of TPX Magnet Grounding Considerations"

The memo transmits my comments on the Preliminary ICD for the WBS13/WBS 42 interface (version dated 7 July 1995).

As a general comment, it remains unclear to me as to where some of the quantitative performance requirements (e.g. TF current, voltage limits, control/measurement precision, etc., etc.) belong. Should they be in the ICD or elsewhere? I'm not sure, and have some concern with regard to these types of requirements appearing in multiple locations without traceability to their source.

The following are specific comments:

- 1) Most important - see above spelling of my name! ✓ *corrected*
- 2) Page 3 of 7, section 1.0, first paragraph, suggest change from
"....and contains switchgear and components to dissipate the energy in the coils in the event of a quench or other abnormal condition."
to
".....contains components to discharge the energy in the coils in the event of a quench or other abnormal condition at a rate consistent with the protection of the coils, contains a ground fault detection system, and contains a means for the regular testing of the integrity of the ground insulation of the TF coil system."
- 3) Page 3 of 7, section 2.0, under TF Program Documents, suggest including drawing no. TPX-D-4201. This is a schematic of the TF system. I would suggest deleting the Xerox of the SDD (your ref. 2.1.2) in favor of a reference to this drawing. I will send you a copy of the drawing under separate cover. It is still OK to reference the SDD; in fact this is essential. I just think that the schematic drawing will provide a better reference than the cartoon sketch from the SDD.
- 4) Page 4 of 7, section 4.1.a, suggest changing from
"Eight TF coils shall be connected in series with each of two parallel sets of buses and leads."

to

"The TF circuit shall consist of two groups of eight series connected TF coils, interleaved in series with two fast discharge circuits and one power supply circuit, in such a way that 1) the same series current is guaranteed to flow through all TF coils during all modes of operation and 2) the loop voltage developed during fast discharge is divided in two equal halves and inserted symmetrically with respect to the two groups of eight coils."

5) Page 4 of 7, section 4.1.b, suggest changing from

"The TF Power System shall include switchgear and dump resistors capable of safely dissipating the energy in the TF Magnet in response to a signal from the TF Magnet Local Instrumentation and Control"

to

"The TF Power System shall contain components to discharge the energy in the coils in the event of a quench or other abnormal condition at a rate consistent with the protection of the coils. The detection of a quench or other abnormal condition and the communication of a request to discharge the TF coils shall be the responsibility of WBS 13. The communication of the request to discharge the magnets from WBS 13 to WBS 42 shall be accomplished via the Critical Data Networks which are the responsibility of the Central I&C WBS 61 and Power Systems Local I&C WBS 41. It shall be the responsibility of WBS 42 to discharge the magnets, once this request is received. WBS 13 shall have the option of selecting a fast or slow discharge, the latter based on the insertion of a total loop resistance equal to 1/2 of the former."

6) Page 4 of 7, section 4.1, suggest adding after 4.1b

"The TF Magnet Local I&C shall include provision to detect the failure of WBS 42 to initiate fast discharge after a time delay of TBD seconds. Upon detection of this event a signal connected directly between WBS 13 and WBS 42 via a dedicated fiber optic channel shall be de-energized, and all (main and auxiliary) devices in WBS 42 associated with the quench protection discharge function shall be actuated."

Note: See reference (1) for a discussion of this.

7) Page 4 of 7, section 4.1, suggest adding after 4.1b

"The TF Power System shall provide the grounding connections for the TF coil circuit. The grounding shall be accomplished through resistors (TBD $\frac{1}{2}$) connected from each pole of each coil interleaf to a ground fault detector and then to ground. The ground fault detector shall inject an AC voltage of TBD volts and TBD Hz on a continuous basis during normal operation and shall measure the leakage current through the ground insulation. In case excessive leakage current is detected a ground fault shall be declared to exist, the ground circuit shall be disconnected, and the TF current shall be ramped to zero in the power supply mode."

Note: See reference (2) for a discussion of this.

8) Page 4 of 7, section 4.1, suggest adding after 4.1b

"The TF Power System shall provide equipment for routine testing of the integrity of the ground insulation (when the TF circuit is de-energized). This equipment shall disconnect the normal ground fault detector components and replace it with a high voltage DC source which can provide a maximum test voltage of TBD volts DC."

9) Page 5 of 7, section 4.4.1.b, suggest adding at the end of the sentence

"...measured at operating (cryogenic) temperature at a frequency of TBD Hz."

10) Page 5 of 7, section 4.4.1.c, suggest adding at the start of the sentence

"During normal operation in the power supply mode, when a fast or slow discharge is not underway, ..."

11) Page 5 of 7, section 4.4.1.d, I would suggest moving this to follow 4.4.1.a, and changing from

"The TF Magnet current shall be constant within +/- TBD% between plasma initiation and discharge."

to

"The TF Power System (WBS 42) and associated control (WBS 46) shall ensure the regulation of the TF current with an error of less than +/- 0.5%. The error specification corresponds to steady state conditions and is defined as the difference between the measured (and averaged, over an interval of TBD seconds) current and the reference current as a percentage of the full scale current, including measurement errors."

12) Page 5 of 7, section 4.4.1.a, I would suggest adding after this section

"The TPX Power System (WBS 42) shall provide redundant TF coil current measurements with an error of less than +/- 0.1%. Current measurement error specification is defined as the difference between the measured value and the actual value as a percentage of the full scale value. These current measurements shall be made available on the Critical Data Network provided by Central I&C (WBS 61)."

13) In general, please replace the word "dump" with "discharge". We have decided that the latter terminology is more graceful.

14) Page 5 of 7, section 4.4.2.b, suggest replacing

"In a "fast dump", the coil protection system shall discharge the magnet at a maximum voltage of 15kV. The TF Power System switchgear shall initiate dump within TBD seconds of receiving a "fast dump" signal. The time constant of the dump circuit shall not exceed 5 s."

with

"During a fast discharge from any value of TF current up to the maximum level specified, the $\int i^2(t)dt$ shall be less than TBD amp²-seconds. This integral shall be measured from the instant that the signal to initiate the discharge is received by WBS 42. Under no circumstances shall the voltage to ground at any point in the TF coil circuit exceed TBD kV".

Note: I would propose that the TBD above be replaced by $\sqrt{1.33 * 7.5kV \cdot 10kV}$.

15) Page 5 of 7, section 4.4.2.c, suggest replacing

"In a "slow dump", the coil protection system shall discharge the TF Magnet at a voltage of 7.5kV."

with

"During slow discharge the total inserted loop resistance shall be 1/2 of that applied during fast discharge (only one of two discharge resistors shall be inserted)."

16) Page 6 of 7, section 4.4.3, suggest replacing

"The TF Magnet and TF Power Systems shall be separately grounded in accordance with TPX Grounding for Equipment and Personnel Safety, reference 2.1.3."

with

"a. The TF Power System shall provide the grounding connections for the TF coil circuit. The grounding shall be accomplished through resistors (TBD 1/2) connected from each pole of each coil interleaf to a ground fault detector and then to ground. The ground fault detector shall inject an AC voltage of TBD volts and TBD Hz on a continuous basis during normal operation and shall measure the leakage current through the ground insulation. In case excessive leakage current is detected a ground fault shall be declared to exist, the ground circuit shall be disconnected, and the TF current shall be ramped to zero in the power supply mode.

b. The TF Magnet system shall provide ground plane electrostatic shields around all coils and associated high voltage conductors. These ground planes shall be connected through ground at an interface point with WBS 47 (TPX Grounding).

c. The TF Power System shall provide no-load line disconnect and grounding switches which isolate the coil interleaves from the power supply system and ground the coil interleaf terminals for purposes of safe access to the TPX machine."

cc:

J French
J Sinnis
B Smith (B&W)

TPX File

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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Central Instrumentation and Control System (WBS 61)**

TPX-ICDP-1361-0001 REVISION A

Date: 7 July 1995

**Prepared By:
B. R. Smith
Babcock & Wilcox Company**

**Concurred By: _____
C. M. Weber
TF Magnet Project Manager**

**Concurred By : _____
S. Davis, PPPL
Central I&C System Manager**

**Approved By: _____
G. Deis, LLNL
Magnet WBS Manager**

**Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager**

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DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First update based on ICD format changes.	A	7 July 1995

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1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF) Magnet System (WBS 13), TPX Central Instrumentation and Control (WBS 61), and other systems that exchange data with the TF Magnet System. The TF Magnet System contains Local I&C capable of sensing and processing data for magnet protection and engineering evaluation. Details concerning TF Magnet to TF Local I&C interfaces are found in the TF Magnet to TF Local I&C ICD (reference 2.3.5). Data will be transmitted to TPX Central I&C to indicate TF Magnet System status and for archiving. No data are required from Central I&C during normal operations.

The TF Magnet and the TF Bus and Leads elements contain sensors for magnet systems diagnostics and coil protection. The sensors terminate at leads outside the respective elements, and include:

- Voltage taps in the coils and current leads
- Temperature sensors
- Pressure sensors in the cooling circuits
- Flow meters in the cooling circuits
- Strain gauges in the coil cases and support structure
- Magnetic field sensors.

TF Local I&C is comprised of the following:

- Sensor interfaces, including signal conditioners (excitation sources and signal amplifiers), voltage isolation, and cabling
- Data acquisition systems
- Magnet protection system
- Direct interfaces to other systems for magnet protection; these systems include the Cryostat (WBS 15), TF Power System (WBS 42), Plasma Diagnostics (WBS 62), and Cryogenic Equipment (WBS 72).
- Interface with TPX Central I&C for magnet status display and data archiving.

The TF Local I&C electronic assemblies are installed, and interconnections between the various elements are made under the TPX Assembly and Installation element (WBS 17) and are covered in the TF Magnet System to Tokamak Assembly and Installation ICD (reference 2.3.4). Cable routings from the tokamak to the control room are also covered in the TF Magnet to Tokamak Assembly and Installation ICD. Cable penetrations of the cryostat are covered in the TF Magnet System to Cryostat ICD (reference 2.3.1).

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

2.1.1 TPX Toroidal Field Magnet System Design Description, dated March 16, 1993

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2.1.2 TF Local I&C Design Description, dated TBD

2.1.3 TPX Grounding for Equipment and Personnel Safety, 94-940429-PPPL/WRauch-01, dated May 26, 1994

2.1.4 [PPPL/LLNL Drawings -- TBD]

2.2 Specifications and Standards

TBD

2.3 Contractor Documents

2.3.1 TPX-ICDP-1315-0001: TF Magnet (WBS 13) to Cryostat (WBS 15) Interface Control Document

2.3.2 TPX-ICDP-1342-0001: TF Magnet (WBS 13) to TF Electrical Power System (WBS 42) Interface Control Document

2.3.3 TPX-ICDP-1372-0001: TF Magnet (WBS 13) to Cryogenic Equipment (WBS 72) Interface Control Document.

2.3.4 TPX-ICDP-1342-0001: TF Magnet (WBS 13) to Tokamak Assembly and Installation (WBS 17) Interface Control Document.

2.3.5 TPX-ICDS-133-136-01: TF Magnet (WBS 13) to TF Local I&C (WBS 136) Interface Control Document

3.0 RESPONSIBILITIES

3.1 TF Magnet Element (WBS 133): Prepare and maintain this document. Design, fabricate, and verify the TF Magnet in conformance with the requirements stated herein.

3.2 TF Local I&C Element (WBS 135): Design, integrate, and verify the TF Local I&C in conformance with the requirements stated herein.

3.3 TPX Central I&C Element (WBS 61): Procure, integrate, and verify TPX Central I&C in conformance with the requirements stated herein.

4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. Other than electrical signal connections, there are no mechanical or fluid interfaces between the TF Local I&C system and other systems.

4.1.1 Sensors

The TF Magnet and TF Bus and Leads elements shall contain the sensors listed in Table 4-1. All sensors (except flow meters) shall be redundant. Figure 2.4.1-1 shows the sensor locations associated with each TF Magnet coil.

Table 4-1 TF Magnet Sensors

<i>Sensor Type</i>	<i>Location</i>	<i>Quantity</i>
Voltage tap (inductive)	Fluid connection to double pancake (2 x 6 x 16)	192
Voltage tap (inductive)	End-to-end coil voltage (2 x 16)	32
Voltage tap (non-inductive)	Co-wound in conductor insulation (2 x 16)	32
Voltage tap (non-inductive)	Co-wound with superconducting cable (2 x 16)	32
Voltage tap (non-inductive)	Coil interconnecting joints (2 x 14)	28
Voltage tap (non-inductive)	Coil-to-bus interconnections (2 x 4)	8
Voltage tap (non-inductive)	Gas-cooled leads at 4 K-300 K transition (2 x 4)	8
Temperature sensor	Helium inlet and outlet manifolds (2 x 4)	8
Temperature sensor	Helium outlet at gas-cooled leads (2 x 4)	8
Fiber-optic temp. sensor	Co-wound with superconducting cable (5 x 16)	80
Pressure transducer	Helium inlet and outlet manifolds (2 x 2)	4
Flow meter (dif. pressure)	Helium inlet to each double pancake (6 x 16)	92
Flow meter (dif. pressure)	Helium inlet to buses (1 x 4)	4
Flow meter (dif. pressure)	Helium outlet at gas-cooled leads (1 x 4)	4
Strain gauge	TF coil cases and structure (2 x 100)	200
Magnetic field (Hall probe)	Each quadrant (2 x 4)	8

4.1.2 Sensor Interfaces

Sensor interfaces include signal conditioners (excitation sources and signal amplifiers), voltage isolation, and cabling, as shown in Figure 2.4.1-2. All signal conditioning shall be outside the cryostat to allow periodic calibration of the transducers.

- a. Sensors requiring the same excitation shall be powered by common excitation sources. TBD number of sensors have millivolt-level full-scale output signals that are amplified for data acquisition.
- b. Excitation sources for the sensors used in the protection systems shall be monitored by the data acquisition system to allow correction of source calibration errors and detection of failures during normal operations.

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- c. Voltage isolation shall consist of:
 - 1. A voltage clamp/filter, voltage-to-frequency converter, and fiber-optic driver (LED) at the transmitters (the transmitters shall be powered by TBD shielded-isolation power transformers);
 - 2. A fiber-optic link from the signal conditioning and isolation systems to the control room; and
 - 3. Fiber-optic receivers with frequency-to-voltage converters in the control room.
- d. The magnet voltage taps shall have separate isolation channels to accommodate the different common-mode voltages present on each.
- e. The pressure and temperature sensors shall be physically isolated from the magnet voltages such that there are no common-mode voltage concerns.
- f. Cables for all magnet diagnostics originating within the cryostat shall be routed through the cryostat to the closest location at which the Signal Conditioning and Isolation Systems (SCIS) can be placed. This location is TBD.

4.1.3 Data Acquisition Systems

Two data-acquisition systems shall be provided:

- a. One system shall monitor only those signals required for the coil protection system. These data shall be used for quench and fault detection only and are not stored. During magnet operation, this system shall sample all protection diagnostics at a rate of 10-20 Hz.
- b. The second system shall monitor all magnet system signals for data storage, and shall provide redundancy to the first system if it fails.

4.1.4 Magnet Protection System

The magnet protection system shall detect normal zones in the coils or in the buses by analysis of sensor data, and shall initiate discharge sequences to prevent damage to the magnet.

- a. The time to detect a quench or other fault and initiate a command to the TF Power System to activate the fast dump circuit(s) shall not exceed TBD s.
- b. The magnet protection system shall be fault tolerant, with multiple sensors and detection circuits. The output of each detector shall be used in control logic that requires fault signals from two or more detectors before a fast-dump sequence is initiated. Quench detectors shall include:
 - 1. Resistive voltage across taps on the coils and current leads
 - 2. Loss of coolant flow, or flow reversal, in the coil and bus manifolds
 - 3. Temperature rise in the coil measured by fiber-optic sensors.

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- c. The magnet protection system shall be fail safe, such that if the interface to the TF Power System is broken, or if local power is lost at the protection system in the control room, then a fast dump shall be initiated in the TF Power System.
- d. In the event of other faults, depending on severity, the magnet protection system shall initiate a slow dump or a normal discharge, in which the magnets are ramped down under power-supply control. Such faults shall include:
 - 1. Loss of cryostat vacuum
 - 2. Fault in TF Power System
 - 3. Fault in Cryogenic Equipment
 - 4. Fault in plasma current or position.

4.1.5 Interfaces with Other Systems

TF Local I&C shall have interfaces with the following systems, all implemented with direct, hardwired connections.

- a. TF Local I&C (WBS 135) shall interface with TPX Central I&C (WBS 61) for magnet status display and data archiving.
- b. TF Local I&C (WBS 135) shall interface with the Cryostat (WBS 15) to receive a signal indicating degradation of the cryostat vacuum level.
- c. TF Local I&C (WBS 135) shall interface with the TF Power System (WBS 42) to transmit magnet discharge sequence commands, and to receive a signal indicating a power system fault condition.
- d. TF Local I&C (WBS 135) shall interface with Plasma Diagnostics (WBS 62) to receive a signal indicating a plasma fault condition.
- e. TF Local I&C (WBS 135) shall interface with the Cryogenic Equipment (WBS 72) to receive a signal indicating a fault in the cryogen supply.

4.1.6 Monitoring and Control

- a. TF Local I&C shall provide for operator-selected display of magnet system status data, and manual control of magnet charging and discharge sequences, at work stations in the TPX Control Room.

4.2 Mechanical Interfaces

- a. The signal conditioning and isolation system shall require TBD rack bays at a location TBD.

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1361-0001
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- b. The data acquisition, magnet protection, and monitoring and control functions shall require TBD rack bays and two work stations in the TPX Control Room.
- c. Cable routing and supports shall be as specified in the TF Magnet to Tokamak Assembly and Installation ICD (reference 2.3.4).
- d. Instrumentation cable penetrations of the cryostat shall be as specified in the TF Magnet to Cryostat ICD (reference 2.3.1).
- e. Cable insulation within the cryostat shall withstand TBD radiation levels.

4.3 Fluid Interfaces

None.

4.4 Electrical Interfaces

4.4.1 Central I&C Data Format

- a. Data shall be transmitted from TF Local I&C to TPX Central I&C for display and archiving as a multiplexed digital stream with characteristics TBD.
- b. During magnet cool-down, initial operations, and periodic system testing, data from all channels (450-500), with sample rates as high as 100 Hz, are passed to Central I&C for processing and archiving. The data rate to Central I&C shall not exceed TBD.
- c. During normal tokamak operations, a subset of the data channels (350-400) with sample rates as high as 10-20 Hz is passed to Central I&C for processing and archiving. The data rate to Central I&C shall not exceed TBD.
- d. The data range, sensitivity, units, and sample rates for each sensor shall be as specified in Table TBD.

4.4.2 Discrete Signal Formats

- a. Discharge sequence signals to the TF Power System shall have a format TBD.
- b. Fault signals to the TF Local I&C shall have a format TBD.

4.4.3 Local Power Requirements

- a. Electronics for the signal conditioning and isolation systems shall require 110 VAC, 60 Hz power not to exceed TBD W.
- b. Electronics for the data acquisition, magnet protection, and monitoring and control functions shall require 110 VAC, 60 Hz power not to exceed TBD W.

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4.4.4 Grounding

- a. The TF Magnet System including TF Local I&C, and interfacing systems, shall be grounded in accordance with TPX Grounding for Equipment and Personnel Safety, reference 2.1.3.

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware and software designs meet the interface requirements specified herein rests with the TF Magnet element, TF Local I&C element, and TPX Central I&C element, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with PPPL and the TPX Systems Integration element.

(TBD matrix for requirements vs. verification method and responsibility)

PRELIMINARY

Figure 4-1 TF Magnet Instrumentation & Control Block Diagram

Figure 2.4.1- I : Double Pancake Diagnostics

Figure 2.4.1- II : Signal Conditioning & Isolation Systems (SCIS)

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1372-0001
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TOKAMAK PHYSICS EXPERIMENT

PRIMARY INTERFACE CONTROL DOCUMENT

**Toroidal Field Magnet System (WBS 13)
to
Cryogenic Equipment (WBS 72)**

TPX-ICDP-1372-0001 REVISION A

Date: 7 July 1995

**Prepared By:
B. R. Smith
Babcock & Wilcox Company**

**Concurred By: _____
C. M. Weber
TF Magnet Project Manager**

**Concurred By : _____
B. Felker, LLNL
Cryogenic Equipment System Manager**

**Approved By: _____
G. Deis, LLNL
Magnet WBS Manager**

**Approved By: _____
W. Reiersen, PPPL
TPX Systems Engineering Manager**

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1372-0001
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DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue	-	4 Jan 1995
	First update based on Feb. 28 Interface Working Meeting at Sunnyvale and telecons between B&W and B. Felker/LLNL	A	7 July 1995

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1372-0001 Rev. A Page 3 of 6
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1.0 SCOPE

This document describes the interfaces between the TPX Toroidal Field (TF) Magnet System (WBS 13) and the Cryogenic Equipment (WBS 72). The Cryogenic Equipment provides a flow of gaseous and supercritical helium to cool and maintain the superconducting magnets at a nominal 5 K during tokamak operation.

The TF Magnet System includes all items with power, even if cryogenics are present, including the magnet coils, superconducting bus, and leads from the bus to the power supply at room temperature. The Cryogenic Equipment includes all items that contain cryogen, but that do not conduct current, including the refrigerator/liquefier, supply and return lines, and manifolds.

Other than fluid connections and manifold supports on the TF Magnet structure, there are no mechanical or electrical interfaces between the Cryogenic Equipment and the TF Magnet System.

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this Interface Control Document, this Interface Control Document shall take precedence.

2.1 TPX Program Documents

2.1.1 TPX Toroidal Field Magnet System Design Description, dated March 16, 1993

2.1.2 Cryogenic Equipment System Design Description, dated TBD

2.1.3 TPX Grounding for Equipment and Personnel Safety, 94-940429-PPPL/WRauch-01, dated May 26, 1994

2.1.4 TPX Helium Heat Loads, 72-950324-LLNL-BFelker-01, dated March 24, 1995

2.1.5 [PPPL/LLNL Drawings – TBD]

2.1.6 Cool Down Helium Flows, 72-950119-LLNL/BFelker-01, dated January 19, 1995

2.2 Specifications and Standards

2.3 Contractor Documents

TBD Drawings

3.0 RESPONSIBILITIES

3.1 TF Magnet Element: Prepare and maintain this document. Design, fabricate, and verify the TF Magnet in conformance with the requirements stated herein.

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1372-0001 Rev. A Page 4 of 6
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3.2 TF Bus and Power Leads Element: Design, fabricate, and verify the TF Bus and Power Leads in conformance with the requirements stated herein.

3.3 Cryogenic Equipment Element: Procure and integrate the cryogenic equipment, and design and fabricate associated coolant lines and manifolds in conformance with the requirements stated herein.

4.0 REQUIREMENTS

4.1 Functional Interfaces

- a. The Cryogenic Equipment shall supply the TF Magnet superconducting coils and bus with gaseous helium during cool-down and warm-up, and with supercritical helium during normal operation.
- b. The fluid circuits shall be as shown in Schematic TBD.
- c. The TF Magnet System shall apply heat loads and resistance to the helium flows within the limits specified herein.
- d. During a magnet or bus quench event, the pressure increase applied to the fluid, and the response of the Cryogenic Equipment, shall be within the limits specified herein.

4.2 Mechanical Interfaces

4.2.1 Envelopes and Attachments

- a. Each 2-coil module of the TF Magnet shall interface at fluid connections to the Cryogenic Equipment supply and return manifolds as shown in LLNL drawing AAA94-100605-01. The fluid connection sizes shall be as follows:
Supply manifold = 3 inches diameter
Return manifold = 3 inches diameter
TF stubs = TBD
- b. The routing and attachments of the Cryogenic Equipment supply and return manifolds on the TF Magnet structure shall be as shown in Drawing TBD (layout drawing). The Cryogenic Equipment Element shall provide all attachment kits and supports for Cryogenic Equipment supported by the TF structure. The TF Magnet Element shall provide attachment surfaces with bolt hole patterns as shown in Drawing TBD.
- c. The TF Magnet superconducting buses shall interface with the Cryogenic Equipment supply at TBD [location, pipe size, etc.].
- d. The TF Magnet current leads shall interface with the Cryogenic Equipment return at the lead vacuum boxes in the spreading room at TBD [location, pipe size, etc.].

4.2.2 Loads

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4.2.2.1 Weights

- a. The TF Magnet System shall support the weight of the Cryogenic Equipment and associated attachment hardware for TF Magnet cooling. The weight of the TF Cryogenic Equipment shall not exceed TBD.
- b. The TF Magnet System shall support TBD weight for PF coil cooling equipment and associated attachment hardware.

4.2.2.2 Differential Contraction Loads

- a. The Cryogenic Equipment attachment support shall accommodate any differential thermal contraction due to TF Magnet cool-down, warm-up and normal operation.

4.2.3 Thermal Interfaces

- a. The maximum heat loads applied to the helium flow shall be as described in the TPX Helium Heat Load tables (Ref. 2.1.4).

4.3 Fluid Interfaces

4.3.1 Cool-Down

- a. During cool-down, the Cryogenic Equipment shall supply a flow of gaseous helium to the TF Magnet System according to the table in "Cool Down Helium Flows" reference 2.1.6.

4.3.2 Normal Operation

- a. During operation, the Cryogenic Equipment shall deliver 5 K supercritical helium to the TF Magnet at 3.91 grams/sec (each channel) with an inlet pressure of 6-8 atm. and an outlet pressure of 2.5- 3 atm.
- b. The allocation of flow, pressure drop, and heat load to the coils, bus, and plumbing shall be as shown in Schematic TBD. The maximum flow imbalance between TF coils shall be no greater than TBD.

4.3.3 Warm-Up

- a. During warm-up, there shall be less than 50 K temperature difference in the flow through the TF Magnet System.

4.3.4 Quench

- a. During a quench in a TF coil, the pressure rise at the interface between the coil and the Cryogenic Equipment shall not exceed TBD, and the heat energy applied to the flow shall not exceed TBD J.

TPX	INTERFACE CONTROL DOCUMENT PRELIMINARY	TPX-ICDP-1372-0001 Rev. A Page 6 of 6
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- b. During a quench in the TF Bus or Leads, the conditions shall not exceed those of a TF coil quench; the TF Bus and Leads shall be capable of withstanding these conditions.
- c. Overpressure relief valves shall be provided on the Cryogenic Equipment manifolds at locations shown in Drawing TBD. Inlet relief pressure shall be set at a maximum of 25 atm., and outlet relief shall be set at the maximum dewar pressure of 4 atm.

4.3.5 Bus-Nitrogen Shields

- a. The Cryogenic Equipment shall supply liquid nitrogen to thermal shields in the Magnet Bus at a temperature of 77 K, a pressure of TBD, and with a mass flow rate of TBD [to either or both of the bus conduits].
- b. The locations of the LN2 supply and return connections are TBD. The details of the connections (pipe size, etc.) are TBD.

4.4 Electrical Interfaces

4.4.1 Isolation

- a. The TF Magnet System and the Cryogenic Equipment shall be electrically isolated from each other, and shall be grounded in accordance with TPX Grounding for Equipment and Personnel Safety (reference 2.1.3).
- b. Isolators shall be provided as part of the TF Magnet System. Leakage current across any isolator shall be less than TBD.

5.0 INTERFACE VERIFICATION

Responsibility for verification that the hardware meets the interface requirements specified herein rests with the TF Magnet element, TF Bus element manager, and Cryogenic Equipment element manager, respectively. Responsibility for verification of compatibility and performance of the integrated system rests with LLNL and the TPX Systems Integration Subcontractor.

(TBD matrix for requirements vs. verification method and responsibility)

LLL2PPL/95/2-95/CRYO-FLOW-SHT1

[illegible]

Interface Control Document Attachment

TF Magnet (WBS 13) to Cryogenic Equipment (WBS 72) ICD

The following pages contain comments to the July 7, 1995 version of the Interface Control Document. These comments include corrections and data for TBD information pertaining to the July 7 status of interface design. Comments that pertain to recent design changes are being compiled for review and discussion during the next phase of work.

Comments to July 7, 1995 TF Magnet/Cryogenic Equipment ICD

From: Brian Felker/LLNL

Received: 31 July 1995 via telephone

4.2.1.a

Helium stub sizes (from G. Markham/B&W):

inlet = 1 inch OD with .065 inch wall

outlet = .75 inch OD with .065 inch wall

4.3.2.b

Maximum flow imbalance shall be $3.91 \text{ g/s} \pm 20\%$ per channel.

4.3.5.a

...mass flow rate shall be TBD per bus.

REVISIONS			
ZONE	REV	DESCRIPTION	DATE
		APPROVED

PRELIMINARY

UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES	
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TOLERANCES OF DECIMALS	± 0.01
1. BREAK ALL SHARP CORNERS	2. DO NOT SCALE THIS DRAWING
3. DIM. TO ANGLES Y14.00 - 1992	4. MAX. ALL MACHINING SURFACES

THIS IS A CAD GENERATED DRAWING, DO NOT MAKE MANUAL REVISIONS OR ALTERATIONS.	
CONTRACT NO.	B235308
APPROVALS	DATE
DESIGN	9/28/92
CHKD	9/28/92
APP'D	9/28/92
REV	DATE
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BABCOCK & WILCOX	
LYNCHBURG, VIRGINIA 24505	
TF MAGNET OCTANT HYDRAULIC CIRCUIT	
SIZE/SCALE	1/4" = 1'-0"
DRAWING NO.	C-1333102
REV	PO
SCALE	SHEET

TOKAMAK PHYSICS EXPERIMENT (TPX)

**TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE**

Contract B235308

SDRL 20
Configuration Item Specifications
August 9, 1995
13-950809-BW-RBatchelder-01

Babcock & Wilcox
Accelerator & Magnet Systems
PO Box 785
Mt. Athos Road
Lynchburg, VA 24505

Approved for Submittal by:
C.M. Weber, TPX Project Mgr.

PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

TF MAGNET COIL SPECIFICATION

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

TPX-SPEC-133-0001
REVISION 0

Prepared for: the University of California
Lawrence Livermore National Laboratory
Subcontract B235308, SDRL 20

Prepared by: the Babcock & Wilcox Company
NNFD, Accelerator and Magnet Systems
Mt. Athos Road, Lynchburg, VA 24505

The original document is on file at B&W.
It was prepared and signed by:
It was approved and signed by:
It was approved and signed by:
It was approved and signed by:
It was approved and signed by:
It was approved and signed by:

R.R. Batchelder, B&W Systems Engineering
R.J. Kunz, B&W TPX Systems Engineering Manager
T.A. Antaya, B&W TPX Design Engineering Manager
C.M. Weber, B&W TPX Project Manager
E.W. Southwick, LLNL QA Manager
G.A. Deis, LLNL Magnet WBS Manager

SIGNATURE SHEET

Prepared by:
R.R. Batchelder, B&W Systems Engineering

Approved by:
R.J. Kunz, B&W TPX Systems Engr. Mgr.

Approved by:
T.A. Antaya, B&W TPX Design Engr. Mgr.

Approved by:
C.M. Weber, B&W TPX Project Manager

Approved by:
E.W. Southwick, LLNL QA Manager

Approved by:
G.A. Deis, LLNL Magnet WBS Manager

DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue		

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1. SCOPE

This document specifies the performance, design, and quality assurance requirements for the superconducting TF Magnet Coil, part of the Toroidal Field Magnet System for the Tokamak Physics eXperiment (TPX).

This specification defines parameters that will be verified by inspection and test at room temperature during coil manufacturing. Coil design criteria that can be verified only by analysis and test at the TF Magnet System level are specified in the TF Magnet System Requirements Document, TPX-SPEC-013-0001 (reference 2.5).

The criteria defined herein apply to the completed-coil, including insulation, conductive ground wrap, helium coolant stubs, and end terminations. The criteria may also be applied to earlier process steps as appropriate.

2. APPLICABLE DOCUMENTS

The following documents of exact issue shown shall apply to the extent referenced herein. In the event of conflict between the referenced document and this specification, the following order of precedence shall prevail:

1. TPX Program Documents marked with an asterisk * (2.1 - 2.6, 2.12, and 2.13)
 2. This specification
 3. Other documents.
-
- 2.1* TPX General Requirements Document, TPX-RQMT-GRD, Rev 1
 - 2.2* Tokamak System Requirements Document, TPX-RQMT-SRD, draft A
 - 2.3* TPX Structural and Cryogenic Design Criteria, TPX-STND-001 Rev 1
 - 2.4* TPX Grounding for Equipment and Personnel Safety, TPX-STND-004, Rev 0
 - 2.5* TPX TF Magnet System Requirements Document, TPX-SPEC-013-0001, Rev 0
 - 2.6* TPX TF Superconductor Specification, TPX-SPEC-132-0001, Rev 0, dated TBD
 - 2.7 TPX Coil Winding Equipment Specification, TPX-SPEC-133-0002, Rev 0
 - 2.8 TPX Coil Reaction Equipment Specification, TPX-SPEC-133-0003, Rev 0
 - 2.9 TPX Coil VPI Equipment Specification, TPX-SPEC-133-0004, Rev 0
 - 2.10* LLNL TPX Quality Assurance Plan, TPX-LLNL-PLAN-002, Rev 1
 - 2.11* PPPL Environmental, Safety, and Health Implementation Plan, Annex II to TPX-PLAN-PMP, Rev 0
 - 2.12 MIL-STD-490A, Specification Practices

3. REQUIREMENTS

3.1 Critical Item Definition

- a. The TF Magnet Coil Critical Item is one of 16 coils arranged in a toroidal configuration in the TF Magnet System, defined in the TF Magnet System Requirements Document, TPX-SPEC-013-0001 (reference 2.5). The TF Magnet System provides the toroidal field to contain the tokamak plasma.
- b. The size and shape of the TF Magnet Coil, and its number of turns, shall be as defined in 3.2.2.1 herein.
- c. The TF Magnet Coil shall be fabricated from Nb₃Sn superconducting cable-in-conduit-conductor (CICC), defined in TPX-SPEC-132-0001 (reference 2.6). The CICC includes co-wound quench detection instrumentation.
- d. The TF Magnet Coil ends shall be terminated in temporary tooling that provides a pressure and leak-tight closure, and that enables access to instrumentation leads co-wound with the CICC for functional testing.

3.2 Characteristics

3.2.1 Performance

3.2.1.1 Electrical Characteristics

- a. The TF Prototype Magnet Coil shall withstand a static voltage from conductor to ground wrap of 16 kV for 60 sec; following coils shall withstand 7.5 kV for 60 sec. The voltages shall be applied at room temperature and in air, and the net coil leakage current shall not exceed 100 μ A. [SCDC §II-1.1]
- b. The ringing response of the coil to a voltage impulse shall be consistent with the response of a nominal coil, which shall exhibit decay to 10% of the initial voltage amplitude in 2.0 sec. [source TBD]
- c. The nominal room temperature inductance of the TF Magnet Coil shall be 50.7 mH. The inductance of any coil shall not exceed a variation of 0.1% from the mean of previously tested coils, at the same stage of manufacture. [source TBD]
- d. The nominal end-to-end room temperature resistance of the TF Magnet Coil shall be 0.134 Ω . The resistance of any coil, adjusted for end length variations, shall not exceed a variation of 1.0% from the mean of previously tested coils. [source TBD]

3.2.1.2 Pressure and Leak Rate Characteristics

- a. The TF Magnet Coil shall withstand a pressure of 25 atm., applied internal to the CICC with end terminations and with the helium stubs plugged. [source TBD]
- b. The leak rate from the TF Magnet Coil at ambient shall not exceed 10^{-5} torr l/sec. The leak rate from any helium stub weld, following a local cold shock to 80 K, shall not exceed 10^{-7} torr l/sec. [source TBD]

3.2.1.3 Hydraulic Characteristics

- a. The pressure drop in any single coolant circuit at room temperature shall not exceed **TBD** psia, measured with helium at an inlet pressure of **TBD** psig and flow of **TBD** g/sec. A single coolant circuit is defined as the CICC in a double pancake between consecutive coolant stubs, or between the first and last stubs and the nearest end termination. [TFSRD §3.1.2.9]
- b. The difference in pressure drop between any two coolant circuits shall not exceed **TBD** psia. [TFSRD §3.1.2.9]

3.2.1.4 Instrumentation Characteristics

- a. Two fiber-optic temperature sensors are co-wound with the CICC; the path length from either end of the conductor to internal sensor terminations shall be nominally 33.3% and 66.7% of the total conductor length. The actual positions of the terminations shall be measured by the time of return of light pulses applied at the sensor ends, with an accuracy of better than 1.0% of the total conductor length. [source TBD]
- b. Six shielded voltage tap cables are co-wound with the CICC. Two of the leads are continuous, and shall have an end-to-end resistance of not more than **TBD** Ohms. The remaining four taps have internal terminations, nominally at 20%, 40%, 60%, and 80% of the conductor length. The actual positions of the terminations shall be measured by the time of return of voltage pulses applied at the sensor ends, with an accuracy of better than 1.0% of the total conductor length. [source TBD]

3.2.2 Physical Characteristics

3.2.2.1 Coil Dimensions

- a. The TF Magnet Coil shall have a total of 84 turns, comprised of 12 pancake layers of 7 turns each, wound with one continuous length of CICC. [SRD §3.7.3]
- b. The TF Magnet Coil shall have dimensions at room temperature and after reaction in accordance with Drawing D-1335100. [source TBD]
- c. The spacing between turns of the TF coil shall be in accordance with Drawing E-1335000. [source TBD]
- d. The geometric location of the outer conduit surfaces shall be measured after reaction and insulation, and shall be located with respect to fiducial marks on the coil with an accuracy of ± 0.005 inch. [source TBD]

3.2.2.2 Cooling Flow Path

- a. Each TF Coil shall have stubs installed in the layer-to-layer transition region in accordance with Drawing D-1335500. The stub length shall allow for at least four welded connections to each stub during processing, test, installation, and maintenance.
- b. The flow path of helium coolant shall be as shown in Drawing D-1333102.

3.2.2.3 Grounding

- a. The TF Magnet Coil shall be wrapped with a conductive layer for electrostatic shielding, and to prevent electrostatic field concentrations from damaging the coil insulation. The conductive layer shall be comprised of two parts, each of which shall be electrically continuous except for the area within the magnet lead box and at another diametrically opposed position on the coil. The conductive layers shall be overlapped and separated with a dielectric layer at the location opposite the lead box. Gaps or holes in the conductive layers outside the lead box shall be no larger than 0.050 inch. [source TBD]
- b. The parts of the conductive layer shall each be grounded to the TF Magnet single-point ground in accordance with TPX-STND-004 (reference 2.4). With the ground connections lifted and 110 Vac applied, the leakage current from either part of the conductive layer to the other or to external structure shall not exceed 100 μ A. [source TBD]

3.2.2.4 Critical Flaw Size

- a. The size of any flaw in the surface of the conduit shall not exceed 10% of the wall thickness in depth, except that flaws not more than 0.055 in. in length shall not exceed 20% of the wall thickness in depth. [source TBD]

3.2.2.5 Strain Limit after Reaction

- a. After reaction of the Nb₃Sn superconductor, strain of the conductor due to further processing or handling shall not exceed 0.3%. [SCDC §II-2.11]

3.2.3 Reliability

- a. The probability of failure of any TF Magnet Coil in the operating life of 3.2.1.5, and after exposure to the environments of manufacturing, shipping, assembly, and operation shall not exceed **TBD**.

3.2.4 Maintainability

- a. The TF Magnet Coils shall not be considered maintainable after impregnation of the insulation, except for maintenance of the leads or coolant connections.

3.2.5 Environmental Conditions

3.2.5.1 Shipping and Storage Environments

The TF Magnet Coils shall be designed to withstand the following non-operating conditions during shipment and storage:

- a. Temperature: -31 to 49°C (-24 to 120°F); surfaces exposed to sunlight shall withstand a maximum temperature of 71°C (160°F) [MIL-STD-810E, Methods 501 and 502]
- b. Relative humidity: 10 to 95%, non-condensing
- c. Transportation load: per B&W Standard NEE-1 (reference 2.14)

3.2.5.2 Operating Environments

- a. The TF Magnet Coils shall be designed for combined operating loads in accordance with the TPX Structural and Cryogenic Design Criteria, §I-1 and §I-2 (reference 2.3), at operating temperatures in accordance with the TF Magnet System Requirements Document, §3.2.5.2 (reference 2.5).
- b. TF Magnet Coil materials shall withstand the combined nuclear dose of the TPX Structural and Cryogenic Design Criteria, §II-2.12 (reference 2.3).
- c. The TF Magnet Coils shall be designed to operate in a vacuum as defined in the TF Magnet System Requirements Document, §3.1.2.3 (reference 2.5).

3.2.6 Transportability

- a. TF Magnet Coils shall be designed for transportability between fabrication sites by truck or dolly. The exposed coil leads shall be protected by fixtures at all times to ensure compliance with the strain requirement of 3.2.2.5.
- b. The TF Magnet Coils shall be protected in shipment and storage by covers to prevent direct exposure to rainfall, snow, or blowing sand or dust. Volumes not accessible for cleaning after delivery shall be protected by securely fastened covers or caps.

3.3 Design and Construction

3.3.1 Materials, Processes, and Parts

3.3.1.1 Material Selection

- a. Materials selected for use in the TF Magnet Coils shall be compatible with the strength, temperature, vacuum, impurity control, magnetic permeability, and activation requirements of the intended application. [GRD §1.13]
- b. The magnetic permeability of materials used in the TF Magnet Coils, with the exception of the superconductor sheath, shall not exceed 1.02. [GRD §1.13]
- c. The residual radioactivity of materials used in the TF Magnet Coils shall not exceed Class A low level waste limits as defined in 10 CFR 61, after exposure to the lifetime dosage specified in 3.2.5.2. [GRD §6.0]

3.3.1.2 Weldments

- a. The design of TF Magnet Coil weldments shall conform to the intent of the ASME Boiler and Pressure Vessel Code, Section VIII.
- b. Welding procedures and operator qualifications shall conform to the intent of the ASME Boiler and Pressure Vessel Code, Section IX.

3.3.1.3 Conductor Winding Process

- a. The size and shape of the TF Magnet Coils shall conform to the requirements of 3.2.2.1. The winding tool and program shall compensate for deformation that may occur during bending and superconductor reaction.

- b. The TF Magnet Coils shall be formed in the equipment defined by specification TPX-SPEC-133-0002 (reference 2.7).

3.3.1.4 Helium Stub Installation Process

- a. Coolant stubs shall be installed as shown in Drawing D-1335500.
- b. The process of installing the coolant stubs shall not cause degradation in conductor properties below acceptable levels defined in the TF Superconductor specification, TPX-SPEC-132-0001 (reference 2.6). The temperature at the superconductor during stub welding shall not exceed 500°C. (reference 1411-950724-LLNL-JZbasnik-01)
- c. The process of installing the coolant stubs shall not cause visible contamination within the conductor, and shall be consistent with the pressure, leak rate, and flow impedance requirements of 3.2.1.2 and 3.2.1.3.

3.3.1.5 Conductor Reaction Process

- a. The TF Magnet Nb₃Sn superconductor shall be reacted to diffuse Sn into Nb. The temperature-time profile of the reaction process shall be in accordance with the superconductor specification, TPX-SPEC-132-0001 (reference 2.6). The reaction process shall achieve the specified time-temperature profile within ±5°C.
- b. The reaction process shall occur in the equipment defined by specification TPX-SPEC-133-0003 (reference 2.8).
- c. At no time when the temperature is above 350°C during the reaction process shall the oxygen concentration either within or outside the conductor be greater than 0.1 ppm.
- d. Witness samples shall be cut from the ends of the superconductor prior to reaction, and shall be subject to the same reaction process as the coil. The critical current of the samples tested after reaction shall conform to the requirements of the TF Superconductor specification, TPX-SPEC-132-0001 (reference 2.6).

3.3.1.6 Coil Insulation Process

- a. The TF Magnet Coil insulation system shall be installed as shown in Drawing D-1335000, and shall meet the requirements of the TPX Structural and Cryogenic Design Criteria, §II-3.0 (reference 2.3).
- b. Prior to insulation wrapping, the exterior of the conductor shall be cleaned to remove particulate contamination or burrs that could affect performance of the insulation.
- c. The Vacuum Pressure Impregnation (VPI) process shall be performed with the equipment defined by TPX-SPEC-133-0004 (reference 2.9).
- d. The processes for insulation and VPI shall ensure that voids in impregnation do not exceed the volume of a sphere TBD-inch in diameter; and that no volume of resin larger than a sphere TBD-inch in diameter will be unreinforced by glass fiber.
- e. The processes for insulation and VPI shall ensure that, after loading at levels equivalent to or greater than the levels of 3.2.5.2, there are no cracks through the thickness of the conduit insulating barrier film.

3.3.2 *Reserved*

3.3.3 *Nameplates and Product Marking*

- a. TF Magnet Coil assemblies shall be identified by part number and serial number, in accordance with [TBD by SIS contractor].
- b. The superconducting strand shall be traceable through the coil serial number to specific melt(s) of raw material.
- c. All other materials used in the coil shall be traceable through the coil serial number to specific production lots.

3.3.4 *Workmanship* [MIL-STD-454N, Requirement 9]

- a. The TF Magnet Coils shall be fabricated and assembled in a workmanlike manner, and shall be accurate in dimensions and alignment of parts with respect to the tolerances on the design drawings.
- b. Assemblies and parts thereof shall be cleaned of smudges; loose, spattered or excess solder; weld metal; metal chips and mold release agents; or any other foreign material which might detract from the intended operation, function or appearance.
- c. Screws, nuts and bolts shall show no evidence of cross threading, mutilation, or detrimental or hazardous burrs, and shall be firmly secured. Fastener installation shall conform to the specified type and tightness or torquing.
- d. Wires and cables shall be positioned or protected to avoid contact with rough or irregular surfaces and sharp edges to avoid damage to insulation, conductors, or adjacent parts.
- e. Shielding on wires and cables shall be secured in a manner to prevent contact or shorting of exposed current-carrying parts. The ends of shielding or braid shall be secured to prevent fraying.
- f. Harnesses and cable containment shall be neat in appearance, uniformly applied and positioned to retain critical form factors and breakout locations. The containment means shall not cause the wire or cable insulation to deform so that performance characteristics are adversely affected.
- g. There shall be no evidence of burns, abrading or pinch marks in the insulation that could cause short circuits or current leakage.

3.3.5 *Interchangeability of Components* [MIL-STD-454N, Requirement 7]

Design tolerances shall permit parts and assemblies of the same part number to be used as replacement items without detracting from the specified performance of the parent item.

3.3.6 *Safety*

The TF Magnet System shall be designed in accordance with the TPX Environmental Safety and Health Implementation Plan (reference 2.11).

3.3.7 Human Factors

- a. The design of the TF Magnet Coil and its manufacturing and test methods shall be consistent and compatible with human capabilities to manufacture and test the item and its components in a repeatable, efficient and safe manner. Mature and proven tooling and methods shall be used to the extent possible.

3.4 Documentation

3.4.1 Specifications

Specifications shall be developed by the Supplier to establish the derivation, flow-down, and control of requirements as follows:

- a. Process specifications defining process control parameters and limits, in accordance with MIL-STD-490, Type D, as a guide (reference 2.12).
- b. Material specifications for materials not controlled by established government or industry standards, in accordance with MIL-STD-490, Type E, as a guide (reference 2.12).

3.4.2 Drawings

- a. TF Magnet drawings shall be prepared for delivery in accordance with Project standards and procedures to describe all components of the system, its installation and interconnections. Such drawings shall include detail part drawings, assembly drawings, electrical and fluid schematics, and wiring diagrams adequate for fabrication of the end item, and for installation and maintenance of the system.

4. QUALITY ASSURANCE PROVISIONS

4.1 General

4.1.1 Responsibility for Tests and Inspections

- a. LLNL shall be responsible to the Project for verification of compliance with all requirements of this specification. LLNL shall perform a cold test of a prototype TF Magnet Coil to verify Magnet System performance, as defined in the Quality Conformance Matrix of TPX-SPEC-013-0001 (reference 2.5).
- b. The TF magnet supplier shall be responsible for verification of conformance to coil performance and design requirements by analysis and demonstration; component, material, and process qualification tests; and magnet coil tests at room temperature. The TF magnet supplier shall support prototype coil testing at LLNL and magnet system testing at PPPL.
- c. The TF superconductor supplier(s) shall be responsible for verification of conformance to the requirements of the applicable specifications for strand, cable, and finished CICC.

4.1.2 Special Verifications

- a. Documentation shall be prepared and delivered, including analyses and qualification test or demonstration records, that verify conformance to requirements inherently determined by the design of the TF Magnet Coil or its manufacturing processes. Such verifications shall demonstrate adequate operating margins to assure the operational reliability of the system.

4.1.3 Quality Assurance System

Documentation of conformance to the requirements specified herein shall be provided, prepared within a system that assures the integrity of the data furnished. The system shall include provisions for inspection, maintenance of test and measuring equipment, control of non-conforming material, and record-keeping in accordance with the LLNL TPX Quality Assurance Plan (reference 2.10).

4.2 Quality Conformance Matrix

Verification of the requirements of this specification shall be in accordance with the Quality Conformance Matrix, Table 4-1. The indicated methods of verification are defined as follows:

- a. Analysis: verification by calculation or simulation, including computer modeling based on established material or component characteristics.
- b. Demonstration: observation of functional operation at ambient; or review of design drawings and specifications; or review of data for similar components and applications.
- c. Inspection: measurements of dimensions, time, electrical parameters, etc., performed at ambient with general-purpose instruments; or review of records from prior conformance verification.

- d. Test: verification by physically exercising a component or system under appropriate loads and operating conditions, including measurement and analysis of performance data.

Table 4-1
TF Magnet System Quality Conformance Matrix

<i>Paragraph</i>	<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>	<i>N/A</i>
3.1 Item Definition					X
3.1.1 Prime Item Diagrams			X		
3.2 Characteristics					X
3.2.1 Performance					X
3.2.1.1 Electrical Characteristics				X	
3.2.1.2 Pressure and Leak Rate Characteristics				X	
3.2.1.3 Hydraulic Characteristics				X	
3.2.1.4 Instrumentation Characteristics				X	
3.2.2 Physical Characteristics					X
3.2.2.1 Coil Dimensions			X		
3.2.2.2 Cooling Flow Path			X		
3.2.2.3 Grounding			X		
3.2.2.4 Critical Flaw Size			X		
3.2.2.5 Strain Limit after Reaction			X		
3.2.3 Reliability	X				
3.2.4 Maintainability		X			
3.2.5 Environmental Conditions					X
3.2.5.1 Shipping and Storage Environments	X				
3.2.5.2 Operating Environments	X				
3.2.6 Transportability		X			
3.3 Design and Construction					X
3.3.1 Materials, Processes, and Parts					X
3.3.1.1 Material Selection		X			
3.3.1.2 Weldments		X			
3.3.1.3 Conductor Winding Process		X			
3.3.1.4 Helium Stub Installation Process		X			
3.3.1.5 Conductor Reaction Process		X			
3.3.1.6 Coil Insulation Process		X			
3.3.2 Reserved					X
3.3.3 Nameplates and Product Marking			X		
3.3.4 Workmanship			X		
3.3.5 Interchangeability of Components		X			
3.3.6 Safety		X			
3.3.7 Human Factors		X			
3.4 Documentation					X
3.4.1 Specifications		X			
3.4.2 Drawings		X			

5. PREPARATION FOR DELIVERY

The TF Magnet Coils shall be delivered in place at the manufacturer's facility for integration into the next higher assembly level.

6. NOTES

10. APPENDIX

10.1 Coil Drawings

D-1333102	TF Hydraulic Circuit
E-1335000	TF Winding Pack
D-1335100	CICC Winding
D-1335500	Helium Stub Installation

10.2 Traceability of Requirements

PRELIMINARY

THIS IS A CAD GENERATED DRAWING, DO NOT MAKE MANUAL REVISIONS OR ALTERATIONS.

CONTRACT NO.	B235308	DATE	8/22/08
DESIGNED BY	W. J. WILCOX	CHECKED BY	W. J. WILCOX
APPROVED BY	W. J. WILCOX	DATE	8/22/08
BABCOCK & WILCOX LYNCHBURG, VIRGINIA 24505			
TF MAGNET OCTANT HYDRAULIC CIRCUIT			
DRAWING NO. C-1333102		REV. 00	
SCALE	1"=1'-0"	SHEET	1

U.S. - INCH/POUND

THIRD ANGLE PROJECTION

1/4"

1/8"

1/16"

1/32"

1/64"

1/128"

1/256"

1/512"

1/1024"

1/2048"

1/4096"

1/8192"

1/16384"

1/32768"

1/65536"

1/131072"

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NOTES:

1. REMOVE ALL BURRS. FINISHED PRODUCT SHALL BE FREE FROM FOREIGN MATTER.
2. MATERIAL: SEE PART DRAWINGS.
3. MARK PART NUMBER & SERIAL NUMBER PER BAW SPEC. DWS-XXXXX.
4. MIDDLE PANCAKES OF THE CICC WINDING ARE OMITTED FOR CLARITY.

7	133-5560	0	Ha STUD
6	133-5505	1	Ha STUD ASSEMBLY E
5	133-5504	1	Ha STUD ASSEMBLY D
4	133-5503	1	Ha STUD ASSEMBLY C
3	133-5502	1	Ha STUD ASSEMBLY B
2	133-5501	1	Ha STUD ASSEMBLY A
1	133-5100	1	TF CICC WINDING
ITEM	PART NO.	QTY.	DESCRIPTION

TPX-D-1335500.SH01.P0

PRELIMINARY

THIS IS A CAD GENERATED DRAWING. DO NOT MAKE MANUAL REVISIONS OR ALTERATIONS.

CONTRACT NO. B235308		DATE 8-11-93	
APPROVALS FOR FOR FOR		TITLE TF CICC WINDING ASSEMBLY	
TOLERANCES OF HOLE DIMENSIONS ± 0.005 TOLERANCE OF DEPTH ± 0.005 TOLERANCE OF DEPTH ± 0.005		BABCOCK & WILCOX LYNCHBURG, VIRGINIA 24503	
U.S. - INCH/POUND FIRST ANGLE PROJECTION		DRAWING NO. D131399	
1. SPEC. ALL DIM. UNLESS OTHERWISE SPECIFIED. 2. DIM. TO CENTER UNLESS OTHERWISE SPECIFIED. 3. DIM. TO SURFACE UNLESS OTHERWISE SPECIFIED.		DRAWING NO. D-1335500	
1. SPEC. ALL DIM. UNLESS OTHERWISE SPECIFIED. 2. DIM. TO CENTER UNLESS OTHERWISE SPECIFIED. 3. DIM. TO SURFACE UNLESS OTHERWISE SPECIFIED.		SCALE 1" = 1"	

PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**TPX COIL WINDING
EQUIPMENT SPECIFICATION**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-SPEC-133-0002
REVISION 0**

Prepared for: the University of California
Lawrence Livermore National Laboratory
Subcontract B235308, SDRL 20

Prepared by: the Babcock & Wilcox Company
NNFD, Accelerator and Magnet Systems
Mt. Athos Road, Lynchburg, VA 24505

The original document is on file at B&W.

It was prepared and signed by:

It was edited and signed by:

It was approved and signed by:

It was approved and signed by:

It was approved and signed by:

It was approved and signed by:

It was approved and signed by:

W.C. Young, B&W Manufacturing Engineering

R.R. Batchelder, B&W Systems Engineering

R.J. Kunz, B&W Systems Engineering Manager

R.F. Ryan, B&W TPX Mfg Engineering Manager

C.M. Weber, B&W TPX Project Manager

E.W. Southwick, LLNL QA Engineer

G.A. Deis, LLNL Magnet WBS Manager

SIGNATURE SHEET

Prepared by:
W.C. Young, B&W Manufacturing Engineering

Edited by:
R.R. Batchelder, B&W Systems Engineering

Approved by:
R.J. Kunz, B&W Systems Engineering Mgr

Approved by:
R.F. Ryan, B&W Mfg. Engineering Mgr.

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C.M. Weber, B&W TPX Project Manager

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G.A. Deis, LLNL Magnet WBS Manager

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<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue		

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1. SCOPE

This document specifies the performance design, documentation, and quality assurance requirements for Coil Winding Equipment used in the manufacture of superconducting magnet coils for the Tokamak Physics eXperiment (TPX).

The equipment shall have the flexibility to manufacture eight types of coil for the TPX project, and other types of coil for other projects. The TPX coils are D-shaped and circular with various sizes between 5 ft and 30 ft outside dimensions. Each coil consists of multiple flat pancake layers of cable-in-conduit-conductor (CICC), with various numbers of layers and turns per layer. Alternate layers are wound in a spiral inside-to-outside and outside-to-inside, with manually-formed transitions between layers.

The design and construction of the coil winding equipment shall provide for safe and reliable coil handling and processing, efficiency of operation, and economy of construction. The Coil Winding Equipment will be installed at a single manufacturing facility, and shall be furnished complete including an as-built drawing set and manuals describing system operation and maintenance.

2. APPLICABLE DOCUMENTS

The following documents shall apply to the extent referenced herein. Unless otherwise indicated, the issue in effect on the date of invitation for bid or request for proposal shall apply. In the event of conflict between the provisions of any of the listed documents and this specification, the provisions of this specification shall prevail. Any such conflict shall be brought to the attention of B&W.

1. Occupational Safety and Health Standards, CFR 29, Chapter XVII, Part 1910
2. Joint Industries Conference, Electrical Standards for Mass Production Equipment, EMP.1.1967
3. Joint Industries Conference, Electronic Standards for Mass Production Equipment and General Purpose Machine Tools, EL-1-71
4. National Electrical Code
5. National Fluid Power Association, Hydraulic Fluid Power Systems Standard for Stationary Industrial Machinery, T2.24.1
6. B&W Quality Requirements, QT 9403
7. Dimensioning and Tolerancing, ANSI Y14.5M-1982

3. REQUIREMENTS

3.1 Item Definition

3.1.1 Item Diagram

The Coil Winding Equipment shall include the following major elements, as shown in Figure 3-1:

- a. Despooler - Holds a reel of conductor for payout to the straightener. The despooler shall have two axes of motion: rotational for payout, and along the spool axis to maintain a constant conductor position entering the straightener. The despooler shall be powered to provide resistance to the conductor drive, and to function as a takeup when the system is operated in reverse.
- b. Straightener - Straightens the conductor as it feeds off the spool when forming a coil. Straightening provides a uniform strain and level of cold work in the conduit entering the roll bender. The straightener shall be capable of being operated in reverse as a roll bender to form the conductor for respooling, if required by fault conditions during coil fabrication.
- c. Roll Bender - Forms the required radius of curvature in the conductor at every position along the conductor length. The roll bender shall be located in a fixed position with respect to the straightener, and over the tangent to the winding table. Conductor leaving the roll bender shall spiral down to the coil form on the winding table. The roll bender shall include sensors to continuously measure the length of conductor from the start of the coil to the current bend point, and the as-formed radius. The roll bender shall also include capabilities to prevent deformation of the conductor cross section, and to correct for conductor twist during bending.
- d. Winding Table - Shall support the coil form tool (provided by B&W) and move the coil form in three axes (x , y , θ) to maintain the coil position corresponding to the current bend point directly under the fixed roll bender.
- e. Control System - Shall integrate data defining the required coil shape with real-time machine measurements and operator commands to control the forming operation. The control system shall also record data providing a log of all pertinent coil forming parameters for later quality verification and problem diagnosis.

3.1.2 Interfaces

3.1.2.1 Conductor and Supply Spool Interfaces

- a. The equipment shall form the TPX TF coils using conductor having the dimensions and material characteristics defined in Appendix 10.1.1.
- b. The equipment shall form the TPX PF-1 through -5 coils using conductor having the dimensions and material characteristics defined in Appendix 10.1.2.
- c. The equipment shall form the TPX PF-6 and -7 coils using conductor having the dimensions and material characteristics defined in Appendix 10.1.3.
- d. The equipment shall be compatible with supply spools for the TPX conductor having dimensions and weights as defined in Appendix 10.1.4.

Figure 3-1 Coil Winding Equipment Diagram

3.1.2.2 Coil Form Tooling Interfaces

- a. The winding table shall provide a common attachment interface and clearance for a coil form tool specific to each coil type, and provided by B&W. Tooling drawings are TBD [but will be larger than the coil sizes defined in Appendix 10.2 to provide for external forming guides].
- b. The equipment shall provide clearance for a manual bender provided by B&W, used to form lead and transition bends. The manual bender will be attached to the coil form tooling; the clearance envelope for this tooling is TBD.
- c. The equipment shall provide clearance for a fixture and equipment provided by B&W, used for piercing and welding tubing stubs to the conductor. The fixture and equipment will be attached to the coil form tool; the clearance envelope is TBD.

3.1.2.3 Cleaning and Insulation Wrapping Station Interface

- a. The equipment shall provide an interface for a conductor cleaning and insulation wrapping station for the PF-6 and -7 coils only. The station shall be located on the conductor spiral between the roll bender and the coil form tooling. The envelope and position of the station are TBD.

3.1.2.4 Coil Form Data Interface

- a. Data defining the shape of the coil will be provided by B&W in digital form on a [medium TBD]. The data will be arranged in a table defining the required radius of curvature at discrete locations along the conductor.
- b. The equipment shall read and operate with data [in a format TBD].
- c. Process log data from the equipment control system shall be provided at both RS232 and RS422 output jacks. Output shall be comma-delimited ASCII unless otherwise approved.

3.1.2.5 Facility Interfaces

- a. The layout of the equipment shall be determined by the equipment supplier. The control console and pendant shall be convenient to the winding table. Facility area required shall be minimized.
- b. The facility is serviced by an overhead crane with 15-ton capacity and a 25-ft hook height. Standard web slings for lifting the equipment, tooling, and coils will be provided by B&W. Any special lifting or handling devices required for equipment installation or operation shall be part of the coil winding equipment.
- c. Electrical power will be provided by the facility at 60 Hz, 115 vac single phase; 240 vac three phase; and 480 vac three phase. Power requirements shall be specified by the equipment supplier. Cabling to wall connections, and switchgear at the equipment, shall be part of the equipment.
- d. Shop air will be provided by the facility at 72 to 130 psig. The flow rate and connection shall be specified by the equipment supplier. Tubing to the facility connections, and valving and regulators at the equipment, shall be part of the equipment.

3.1.3 Process Description

- a. A spool of conductor is installed on the despooler, and the appropriate coil form tool is mounted on the winding table. Sufficient conductor is separated from the spool and bent to calibrate the relationship between roll bender parameters and the radius of curvature achieved. Bending calibration data and the coil form data set are loaded, and the equipment is checked out.
- b. A reusable lead is attached to the conductor to thread the straightener. The straightener is jogged sufficiently to thread the roll bender. It is then further jogged to provide the coil lead, which is bent in the plane of the coil and attached to the coil form tool guides.
- c. Layer forming is initiated on the perimeter of the coil containing the leads. As the first layer is formed, the conductor is shaped and seated on the coil form, and restraining clamps are used to secure the conductor to the coil form. A spacer strip is installed manually between succeeding turns. Turn-to-turn transitions to permit nesting of the turns in the plane of the layer are defined in the coil form data set.
- d. The turns of the first coil layer are formed in the above manner until approximately 30° before completion of the final turn. The manually-operated bending tool is installed on the conductor, and the layer-to-layer transition bend is executed. The spacer strip is bent simultaneously with the conductor.
- e. Layer-to-layer spacer plates shaped to fit the contour of the coil are installed to separate the first and second layers.
- f. The turns of the second layer are now formed in the opposite sequence to the first layer.
- g. As defined by the design drawings, the conduit is pierced in alternate transition bends, and a tubular stub for coolant flow is welded to the outer surface.
- h. After completion of the last layer, the manual bending tool is used to form the lead bends. The completed coil is removed from the winding table in its coil form tool; or it is banded and removed from the tool, which remains on the winding table.

3.2 Characteristics.

3.2.1 Performance

3.2.1.1 Coil Forming Accuracy

- a. The variation in spacing between successive coil turns shall not exceed 0.010 inch, as formed by the roll bender and clamped to the coil form tool. The spacing between restraints on the coil form tool will not be less than 18 inches.
- b. Each layer shall be flat within 0.010 inch, after roll bending and placement in the coil form tool.
- c. The roll bender shall correct for twist in the conductor so that the surfaces of any formed conductor are parallel to the adjacent conductor surfaces within the total 0.010

inch tolerances allowed for spacing and flatness. The magnitude of twist compensation shall be determined by the operator and input manually.

- d. Deformation of the conductor cross section due to roll bending (keystoning or crushing of the section) shall not exceed 0.005 inch.
- e. The machine shall measure the conductor length before the roll bender with an accuracy of at least ± 0.020 inch (0.5 mm) within any coil turn. Marks shall be placed on the conductor by the equipment at locations determined by the coil form data set. The marks on all turns in a layer shall align to a nominal coil radius within ± 0.020 inch (0.5 mm).
- f. The winding table shall have a positional repeatability in x- and y- coordinates of 0.040 inch (1 mm) under load at any location on any coil.
- g. The equipment shall contain a gauge capable of verifying table position repeatability and the dimensions of the coil form tool within an accuracy of ± 0.010 in.

3.2.1.2 Throughput

- a. The winding machine shall be capable of forming conductor at a variable speed up to at least 1 meter/minute.
- b. The elapsed time to fabricate a TF coil shall not to exceed 100 hours, as a goal.

3.2.1.3 Reverse Operation

- a. The winding machine shall be capable of removing conductor from the coil form tool, straightening it, and respooling it onto the supply spool. (Manual reconfiguration to accomplish this function is acceptable. This capability is to address fault conditions and is not expected to be used routinely.)

3.2.1.4 Conductor Surface Defects

- a. The winding equipment shall form the required coil configuration without raising burrs or inducing other local surface finish defects in the conductor. The surface finish of the formed conductor shall not exceed 125 microinches (RMS).
- b. The winding machine shall not contaminate the conductor surface with foreign material detectable with the naked eye.

3.2.1.5 Control System

- a. The equipment control system shall be capable of monitoring and controlling all hydraulic, pneumatic, and electrical drive components on the despooler, straightener, roll bender and winding table. The control system shall have self-diagnostic capabilities to detect and identify fault conditions. It shall have data recording and display capabilities to permit manual control, performance verification, machine calibration, and debugging of the control program and machine hardware.
- b. A portable pendant control unit shall be provided, enabling control of critical machine functions from any point around the winding table. The control console and portable pendant shall be ergonomically designed. The operator interface shall be intelligible to a generally skilled laborer with a minimum of training.

- c. The following parameters shall be monitored, recorded and controlled by the machine. If response is not within program limits, an alarm shall be initiated and automatic operation shall be interrupted. A warning shall be issued prior to the alarm and termination of operation, where practicable.

Despooler	Unwind torque Z axis position
Straightener	Conductor drive speed Conductor drive torque
Roll bender	Force on conductor Conductor payout (arc length) Conductor as-formed radius Twist displacement
Winding Table	X and Y axis position of coil center Azimuthal position

- d. The following operator controls shall be provided, as a minimum, at both the portable pendant and the control console:

Auto wind (spring loaded switch)
Jog wind and unwind
Despooler position jog (Z axis)
Roll bend radius manual jog (increase or decrease)
Twist angle manual jog (clockwise or counter-clockwise)
Winding table jogs (X axis, Y axis, and azimuthal)

- e. The following program parameters, as a minimum, shall be accessible to the operator through the control console:

Despooler torque
Calibration data and changes in conductor bending properties
Automatic program interrupt positions (for transition bending and tube stub welding)
Straightener deflection (manual change to programmed setting)

- f. The following program parameters, as a minimum, shall be accessible to a supervisor, identified by password, through the control console:

Leads and lags for initiation of bend radius changes
Changes to the coil form data set
Alarm limits
Any other input necessary to correct for anomalies discovered in coil inspection.

- g. Data displayed at the console shall be in engineering units, and shall include all parameters listed in subparagraph c. plus any other parameters necessary to verify proper operation such as hydraulic fluid temperature and pressure, air pressure, etc.
- h. Data recorded by the control system shall include all alarms, identified by date, time, layer number, turn number and winding table azimuthal position. The measured payout length of conductor in each turn of the coil, and the as-formed radius as a function of payout length shall be recorded. A log of parameter settings and actual values during the execution of the coil winding shall be recorded, tagged by date, time, layer number, turn number and winding table azimuthal position.

- i. The control system shall limit machine access to operators and supervisors identified by valid password. The identity of operators and supervisors on the system, and their times of log-on and log-off, shall be recorded.
- j. The system shall automatically boot up into the control system manual mode on power up. Operating parameters shall be saved in a parameter file so that operation can be continued after a power failure or other fault without loss of accuracy.

3.2.1.6 Operating Cycles and Useful Life

The equipment shall have a useful life consistent with processing no less than 32 coils, with the following quantity by type, in a period of three years:

TF	17
PF-1	3
PF-2	2
PF-3	2
PF-4	2
PF-5	2
PF-6	2
PF-7	2

3.2.2 Physical Characteristics

The equipment shall accommodate the nominal dimensions of the TPX coils, as defined in Appendix 10.2. Actual coil dimensions will be defined in the coil form data set.

3.2.3 Reliability

The winding equipment shall be designed for reliable operation in the expected life of 3.2.1.6 with normal maintenance.

3.2.4 Maintainability

- a. All components subject to periodic preventative maintenance or expected repair within the life expectancy shall be designed for ease of access without excessive disassembly of the machine.
- b. The machine shall be designed such that preventative maintenance is not required more frequently than once every ten complete coil fabrication cycles. Elapsed time for preventative maintenance shall not exceed 8 hours.
- c. The mean corrective maintenance time shall not exceed 12 hours.

3.2.5 Environmental Conditions

The equipment shall be designed for use in a shop environment with temperatures varying from 10 to 35°C (50 to 95°F), and relative humidity of 10 to 95%.

3.3 Design and Construction.

3.3.1 Materials, Processes, and Parts

- a. All parts and materials used in the construction of the equipment shall be suitable for the intended function. Used and reconditioned parts and assemblies may be incorporated into the equipment, provided performance and reliability are not compromised.
- b. Programmable controllers integrated into the control system shall be Allen-Bradley manufacture, and computers shall be Ziatech manufacture unless otherwise approved.
- c. External non-contact surfaces shall be either a corrosion resistant material or shall be sand blasted and painted with a two-component epoxy paint.
- d. Contact surfaces shall be either corrosion resistant or treated with an adherent conversion coating to prevent corrosion.
- e. Hydraulic systems shall be designed and constructed in accordance with the National Fluid Power Association, Hydraulic Fluid Power Systems Standard for Stationary Industrial Machinery, T2.24.1

3.3.2 Electromagnetic Compatibility

The equipment shall be designed for use in a shop environment which includes the operation of heavy-duty electric motors and electric arc welders, as well as sensitive computers and control electronics. The equipment shall not be susceptible to radiated or conducted electromagnetic interference typical of such an environment, nor shall it create interference greater than levels typical of such other equipment.

3.3.3 Nameplates and Product Marking

- a. An identification plate shall be affixed to the side of the winding machine listing the name "TPX Coil Winding Machine", the number of this specification and revision, the manufacturer and manufacturer's identification number, the procurement entity and contract number, a tool identification number to be furnished by B&W, the date of manufacture, and any other relevant information.
- b. All major unit subassemblies shall be permanently identified by the unit descriptor, part number, serial number, supplier, and month and year of manufacture. Replaceable components shall be clearly marked with identifiers traceable to the circuit schematics, parts lists, and other documentation used for maintenance.
- c. Internal wiring shall be identified by wire number traceable to the circuit schematics and wiring diagrams used for maintenance. Terminal blocks shall be provided with markings corresponding to those of the wire and wiring diagrams.

3.3.4 Workmanship

- a. The equipment shall be fabricated and assembled in a workmanlike manner, and shall be accurate in dimensions and alignment of parts with respect to the tolerances on the design drawings. The equipment shall be free of burrs and sharp edges.

- b. Assemblies and parts thereof shall be cleaned of smudges; loose, spattered or excess solder; weld metal; metal chips and mold release agents; or any other foreign material which might detract from the intended operation, function or appearance.
- c. Screws, nuts and bolts shall show no evidence of cross threading, mutilation, or detrimental or hazardous burrs, and shall be firmly secured. Fastener installation shall conform to the specified type and tightness or torquing.
- d. Wires and cables shall be positioned or protected to avoid contact with rough or irregular surfaces and sharp edges to avoid damage to insulation, conductors, or adjacent parts.
- e. Shielding on wires and cables shall be secured in a manner to prevent contact or shorting of exposed current-carrying parts. The ends of shielding or braid shall be secured to prevent fraying.
- f. Harnesses and cable containment shall be neat in appearance, uniformly applied and positioned to retain critical form factors and breakout locations. The containment means shall not cause the wire or cable insulation to deform so that performance characteristics are adversely affected.
- g. There shall be no evidence of burns, abrading or pinch marks in the insulation that could cause short circuits or current leakage.
- h. The machine shall be free of hydraulic and pneumatic leaks, either in service or when idle.

3.3.5 Interchangeability of Components

Design tolerances shall permit parts and assemblies of the same part number to be used as replacement items without detracting from the specified performance of the parent item.

3.3.6 Safety

- a. The design of the equipment shall comply with the Occupational Safety and Health Standards, CFR 29, Chapter XVII, Part 1910; and the National Electrical Code
- b. The equipment design shall minimize hazards to personnel and product. Where the equipment design cannot eliminate hazardous equipment, processes or materials, suitable safety markings, light curtains and/or procedures shall be posted on the equipment.
- c. Protective guards shall be provided to prevent shock, burns or entanglement in the machine by operators. Power and control cabling shall be routed to avoid interference with operators. External surface temperatures shall not exceed 30°C (86°F). Interlocks or safety markings shall be provided where removal of protective features could expose personnel to hazards.
- d. The system shall be designed to fail safe. Control system interlocks shall disable automatic forming when alarm conditions occur and when safety panels or enclosures are removed from hazardous areas. The machine shall not undergo any unplanned movement in the event of power loss, hydraulic disruption or other fault condition.

3.3.7 Human Factors

- a. The design of the equipment shall be consistent with human capabilities to operate and maintain the equipment in an efficient and safe manner, in accordance with good commercial practice.
- b. Controls and indicators shall be located and configured to minimize the probability of human error in operation.
- c. Access to maintainable components, and provisions for removal and replacement thereof, shall permit accurate, efficient and safe maintenance of the equipment.

3.4 Documentation

3.4.1 Drawings

- a. Certified foundation and installation drawings shall be prepared, showing the location and sizes of all services, an outline of the floor area required to clear all machine motions, total net weight, and major individual component weights. Drawings shall also show bolt layout and the purpose of each bolt, isolation requirements, and maximum allowable weights on work piece mounting interfaces.
- b. As-built equipment drawings shall be prepared for delivery in accordance with good commercial practice to describe the system installation and interconnections. The drawings shall include a scaled plan view, front elevation, and end elevation, and shall contain major equipment dimensions and work clearances. The drawings shall also include hydraulic, pneumatic, and electrical schematics and routing diagrams adequate for design and construction of facilities, and for installation and maintenance of the system.
- c. Electrical wiring and schematic diagrams shall be prepared in accordance with the following Joint Industries Conference standards:
 - 1. Electrical Standards for Mass Production Equipment, EMP.1.1967
 - 2. Electronic Standards for Mass Production Equipment and General Purpose Machine Tools, EL-1-71
- d. All drawings shall be prepared using Computer Aided Design methods, and shall be furnished in three hard copy sets and in an electronic format compatible with Intergraph or IGES format. Dimensioning and tolerancing shall be in accordance with ANSI Y-14.5M. Drawings shall be prepared with consistent metric or English units; dual dimensioning is permitted, but if used the metric units shall be shown in parentheses.

3.4.2 Operation and Maintenance Manuals

- a. Technical manuals shall be prepared to describe equipment operation and maintenance functions. The manuals shall enable coil manufacturing personnel with technical skills to independently operate and maintain the equipment with minimal specialized training. Control functions shall be clearly documented in the operating manual and in a help function readily accessible from the control panel. Safety requirements shall also be detailed in the operating manual.

- b. The manuals shall contain or shall reference wiring diagrams and schematics; mechanical layouts; parts lists; and operating, diagnostic, and repair procedures. The manuals shall contain copies of OEM manuals for items incorporated into the equipment for which such manuals are furnished.

3.4.3 Software

- a. Software furnished for equipment control shall be documented with functional descriptions, block diagrams, data item descriptions, and source code listings and compilers for special applications. Special applications shall be written in Microsoft C++ or Allen Bradley Ladder Logic.
- b. Standard operating system and application software shall be furnished with OEM manuals and site licenses for use at B&W's facility. The latest available version of standard software at the time of equipment delivery shall be furnished with the equipment.
- c. Initial data loads shall be documented and furnished with the equipment.

4. QUALITY ASSURANCE PROVISIONS

4.1 General

4.1.1 *Responsibility for Tests and Inspections*

The equipment supplier is responsible for verification and demonstration of compliance with all requirements of this specification. The supplier may use his own facilities or any other laboratory acceptable to the buyer for performance of required tests and demonstrations. The buyer reserves the right to witness any tests and demonstrations performed by supplier, or to perform any inspection, test, or demonstration necessary to assure that the equipment conforms to the specified requirements.

4.1.2 *Special Verifications*

- a. Supplier shall prepare and deliver documentation, including analyses and demonstration records that verify conformance to requirements inherently determined by the design of the equipment.
- b. Final verification and acceptance of the equipment shall be based on processing of at least two layers of a TF coil (fabricated with copper cable in place of superconductor) after equipment installation at B&W's facility.

4.1.3 *Quality Assurance System*

Supplier shall provide documentation of conformance to the requirements specified herein, prepared within a system that assures the integrity of the data furnished. The system shall include provisions for inspection, maintenance of test and measuring equipment, control of non-conforming material, and record-keeping in accordance with B&W QT 9403, Quality Requirements.

4.2 Quality Conformance Matrix

Verification of the requirements of this specification shall be in accordance with the Quality Conformance Matrix, Table 4-1. The indicated methods of verification are defined as follows:

- a. Analysis: verification by calculation or simulation, including computer modeling based on established material or component characteristics.
- b. Demonstration: observation of functional operation at ambient; or review of design drawings and specifications; or review of data for similar components and applications.
- c. Inspection: measurements of dimensions, time, electrical parameters, etc., performed at ambient with general-purpose instruments; or review of records from prior conformance verification.
- d. Test: verification by physically exercising a component or system under appropriate loads and operating conditions, including measurement and analysis of performance data.

Table 4-1
TPX Coil Winding Equipment Quality Conformance Matrix

<i>Paragraph</i>	<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>	<i>N/A</i>
3.1 Item Definition					X
3.1.1 Item Diagram		X			
3.1.2 Interface Definition					X
3.1.2.1 Conductor and Supply Spool Interface		X			
3.1.2.2 Coil Form Tooling Interfaces		X			
3.1.2.3 Cleaning and Insulation Wrapping Station Interface		X			
3.1.2.4 Coil Form Data Interface		X			
3.1.2.5 Facility Interfaces		X			
3.1.3 Process Description					X
3.2 Characteristics					X
3.2.1 Performance					X
3.2.1.1 Coil Forming Accuracy		X		X	
3.2.1.2 Throughput		X		X	
3.2.1.3 Reverse Operation		X		X	
3.2.1.4 Conductor Surface Defects			X		
3.2.1.5 Controls and Data Logging		X		X	
3.2.1.6 Operating Cycles and Useful Life		X			
3.2.2 Physical Characteristics					X
3.2.3 Reliability		X			
3.2.4 Maintainability		X			
3.2.5 Environmental Conditions		X			
3.3 Design and Construction					X
3.3.1 Materials, Processes, and Parts		X			
3.3.2 Electromagnetic Compatibility		X			
3.3.3 Nameplates and Product Marking			X		
3.3.4 Workmanship			X		
3.3.5 Interchangeability of Components		X			
3.3.6 Safety		X			
3.3.7 Human Factors		X			
3.4 Documentation					X
3.4.1 Drawings		X			
3.4.2 Manuals		X			
3.4.3 Software		X			

5. PREPARATION FOR DELIVERY

The equipment shall be delivered in place at B&W's facility.

6. NOTES

10. APPENDIX

10.1 Conductor Characteristics

10.1.1 TF Conductor

Conduit Material: Incoloy 908

Room temperature properties of Incoloy 908

	<i>Mill Anneal</i>	<i>Mill Anneal + 20% cold work</i>
Young's Modulus		181 GPa (26.3 x 10 ⁶ psi)
Shear Modulus		70 GPa (10.2 x 10 ⁶ psi)
Bulk Modulus		146 GPa (21.3 x 10 ⁶ psi)
Poisson's Ratio		0.293
Yield Strength	389 MPa (56.5 ksi)	1,025 Mpa (148.8 ksi)
Ultimate Tensile Strength	717 Mpa (104.1 ksi)	1,135 Mpa (164.7 ksi)

Source: INCO literature and Incoloy Alloy 908 Data Handbook, MIT, Plasma Fusion Center, March 1994

10.1.2 PF-1 to -5 Conductor

Conduit Material: Incoloy 908 (see 10.1.1 for properties)

PF1 TO PF5 CONDUCTOR

10.1.3 PF-6, -7 Conductor

Conduit Material: 316 LN Stainless Steel

PF6 TO PF7 CONDUCTOR

10.1.4 Conductor Supply Spools

Conductor supply spools for each coil type will be approximately 10 ft in diameter x 10 ft in height. The conductor length, approximate total weight, and number of layers on the spool are as follows:

<i>TPX Coil</i>	<i>Conductor length m (ft)</i>	<i>Total spool weight kg (lbs)</i>	<i>No. of layers on spool</i>
TF	1,200 (3,900)		
PF-1			
PF-2			
PF-3			
PF-4			
PF-5			
PF-6			
PF-7			

10.2 TPX Coil Characteristics

<i>Coil Designation</i>	<i>Figure #</i>	<i>Weight (lbs)</i>
TF	10-1	16,654
PF-1	10-2	6,820
PF-2	10-2	5,940
PF-3	10-2	4,620
PF-4	10-2	4,620
PF-5	10-3	9,700
PF-6	10-4	TBD
PF-7	10-4	TBD

Figure 10-1 TF Coil

COIL TYPE	DIM. "X"	DIM. "Y"
PF1	18.8"	105"
PF2	15"	101"
PF3	9.4"	95"
PF4	9.4"	95"

TOP VIEW

END VIEW

Figure 10-2 PF-1 - PF-4 Coils

TOP VIEW

END VIEW

Figure 10-3 PF-5 Coil

Coil
PF-6
PF-7

Coil outer diam.
307.40 in
349.87 in

Form tool diam.
320.00 in
363.00 in

Figure 10-4 PF-6 and -7 Coils

PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**TPX COIL REACTION
EQUIPMENT SPECIFICATION**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-SPEC-133-0003
REVISION 0**

Prepared for: the University of California
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Prepared by: the Babcock & Wilcox Company
NNFD, Accelerator and Magnet Systems
Mt. Athos Road, Lynchburg, VA 24505

The original document is on file at B&W.

It was prepared and signed by:	W.C. Young, B&W Manufacturing Engineering
It was edited and signed by:	R.R. Batchelder, B&W Systems Engineering
It was approved and signed by:	R.J. Kunz, B&W Systems Engineering Manager
It was approved and signed by:	R.F. Ryan, B&W TPX Mfg Engineering Manager
It was approved and signed by:	C.M. Weber, B&W TPX Project Manager
It was approved and signed by:	E.W. Southwick, LLNL QA Engineer
It was approved and signed by:	G.A. Deis, LLNL Magnet WBS Manager

SIGNATURE SHEET

Prepared by:
W.C. Young, B&W Manufacturing Engineering

Edited by:
R.R. Batchelder, B&W Systems Engineering

Approved by:
R.J. Kunz, B&W Systems Engineering Mgr

Approved by:
R.F. Ryan, B&W Mfg. Engineering Mgr.

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DOCUMENT CHANGE RECORD

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1. SCOPE

This document specifies the performance design, documentation, and quality assurance requirements for Coil Reaction Equipment used in the manufacture of superconducting magnet coils for the Tokamak Physics eXperiment (TPX).

The magnet coils are fabricated from Nb₃Sn cable contained in Incoloy 908 conduit. After a coil is wound, the Nb₃Sn is reacted at elevated temperature for approximately 20 days to diffuse Sn into Nb, forming a superconducting intermetallic. The reaction process must be performed with a specific temperature-time profile at all points on the coil to achieve optimum superconductor properties. Since the Incoloy 908 conduit is susceptible to cracking in the presence of oxygen at elevated temperature, stringent control of the atmosphere within and surrounding the conduit is essential.

The Coil Reaction Equipment includes a vacuum/partial pressure furnace, vacuum pumping system, partial pressurization system, charge purge system, heating and cooling systems, a charge loading system, an automated control and data logging system, and a backup power supply. The reaction equipment shall have the flexibility to react six types of coil for the TPX project, with various combinations of coil types in any furnace charge. The equipment will be installed at a single manufacturing facility, and shall be furnished complete including an as-built drawing set and manuals describing system operation and maintenance.

The TPX coils are D-shaped and circular with various sizes between 5 ft and 16 ft outside dimensions. Each coil consists of multiple flat pancake layers of cable-in-conduit-conductor (CICC), with various numbers of layers and turns per layer. Conductive spacers between the turns and layers are used to improve heat diffusion to the interior of the coil, and heater zones will be located to ensure uniformity and reliability of temperature control.

The coils are high value items whose performance will be compromised by significant variations from the reaction process parameters. The design and construction of the Coil Reaction Equipment shall therefore provide for safe and reliable coil handling and processing, efficiency of operation, and economy of construction.

2. APPLICABLE DOCUMENTS

The following documents apply to the extent referenced herein. Unless otherwise indicated, the issue in effect on the date of invitation for bid or request for proposal shall apply. In the event of conflict between the provisions of any of the listed documents and this specification, the provisions of this specification shall prevail. Any such conflict shall be brought to the attention of B&W.

1. Occupational Safety and Health Standards, CFR 29, Chapter XVII, Part 1910
2. Joint Industries Conference, Electrical Standards for Mass Production Equipment, EMP.1.1967
3. Joint Industries Conference, Electronic Standards for Mass Production Equipment and General Purpose Machine Tools, EL-1-71
4. National Electrical Code
5. National Fluid Power Association, Hydraulic Fluid Power Systems Standard for Stationary Industrial Machinery, T2.24.1
6. B&W Quality Requirements, QT 9403
7. Dimensioning and Tolerancing, ANSI Y14.5M-1982
8. National Fire Protection Association, Standard for Industrial Furnaces Using Special Processing Atmosphere, NFPA 86C-91

3. REQUIREMENTS

3.1 Item Definition

3.1.1 Item Diagram

The Coil Reaction Equipment shall include the following major elements, as shown in Figure 3-1:

- a. Vacuum/Partial Pressure Furnace. The furnace shall be a front loading box furnace equipped with a door that pivots or slides for access to the interior of the chamber. The furnace walls shall be insulated to minimize heat loss, and water cooled to provide a safe external temperature and to expedite cool-down at the end of the reaction cycle. The furnace floor shall support the charge loading system and a work platform.
- b. Vacuum System. The furnace shall be equipped with two parallel vacuum systems which normally work together to establish and maintain the furnace vacuum. When the furnace is operated with a partial pressure of inert gas, one of the vacuum systems will be valved off and the other throttled to reduce gas consumption. Either vacuum system shall be capable of maintaining the specified vacuum in the furnace should the other system fail.

The system shall be equipped with a Residual Gas Analyzer (RGA) on the chamber vacuum manifold, with sensitivity optimized for species with Atomic Mass Units less than 100. A leak checking capability using a helium leak detector or RGA with audible signal shall be provided for the chamber and the gaps between all dual seals. Provisions shall be made for continuous contamination monitoring at the inert gas inlets to the chamber and the charge, and at the charge purge outlet.

- c. Partial Pressurization System. The equipment shall include a chamber feed-through, regulator, valves, a gas scrubber, and plumbing to an inert gas supply, capable of maintaining an inert gas atmosphere in the furnace at a pressure less than one atm. The inert gas supply will be provided by B&W.
- d. Charge Purge System. The equipment shall include chamber feed-throughs, an internal distribution manifold, a gas scrubber, valves, a regulator, and plumbing to an inert gas supply, capable of flowing inert gas to the charge and collecting the purge gas and exhausting it outside the chamber. The inert gas supply will be provided by B&W.
- e. Heater System. The equipment shall include power supplies, distribution cables and chamber feed-throughs, and radiant heater banks arranged in independent zones; the number and locations of zones shall be determined by the supplier for each charge configuration, based on the temperature uniformity and reliability requirements. Feed-throughs and external cabling to the control system shall also be provided for up to 36 thermocouples attached to the charge and provided by B&W.
- f. Chamber Wall Cooling System. The equipment shall include a closed-loop water circulation system which maintains the furnace walls above room temperature to prevent condensation when the furnace is idle, and near room temperature for safety when the furnace is in operation. The system shall include necessary water conditioning equipment and a cooling tower located outdoors and protected against freezing.

- g. **Internal Cooling System.** The equipment shall include air-cooled panels within the chamber to expedite charge cool-down by radiant heat transfer. The cooling circuit shall contain necessary blowers and ducts to an outdoor exhaust, and shall have provisions for evacuation, isolation, and filling with helium for leak checking before the introduction of air.
- h. **Charge Loading System.** The equipment shall include a transfer cart for loading the charge, and guide rails extending outside the furnace. The transfer cart shall interface with fixtures provided by B&W that support the charge. If the transfer cart is removed during reaction, stands shall be provided to support the charge and jacking devices to transfer the charge between the cart and the stand. The rails outside the furnace shall be movable to provide clearance for closure of the furnace door and to permit storage when not in use.
- i. **Control and Data Logging Systems.** The equipment shall include a computer or programmable controller, peripheral devices, interconnections, and software capable of automated execution of the reaction cycle and recording data that provide a log of process parameters. The system shall control the power applied to each heater zone in response to charge temperature variations from a stored program. The system shall also actuate valves and pumping systems to maintain the chamber vacuum or atmosphere in accordance with a stored program. The system shall monitor and record temperatures from the charge mounted thermocouples, and the furnace vacuum level or partial pressure level. The system shall contain self diagnostics, logic to avoid catastrophic temperature regimes, and sufficient redundancy to tolerate electronic part faults. The system shall be equipped with a manual override for process changes and fault response by the operator.
- j. **Backup Power System.** The equipment shall contain a backup power system capable of continuously operating all systems except the heating and cooling systems in the event of a facility power disruption.

Figure 3-1a Reaction Equipment Plan and Side Views

Note: Detail "A" is representative of a typical wall section.

Figure 3-1b Reaction Equipment Front View

3.1.2 Interfaces

3.1.2.1 Charge Interfaces

- a. The sizes and weights of individual coils and their support fixtures will be as defined in Appendix 10.1. The equipment shall be capable of reacting one or a combination of coils, including but not limited to two TF coils, or one TF and one of any PF type.
- b. The interface between the coil support fixture and the charge loading system shall be as shown on drawing TBD.
- c. Internal heater banks may be attached to the coil support fixture, at a mechanical interface that is TBD.
- d. Thermocouples attached to the charge shall be type K. The electrical connection at the signal feed-through is TBD.
- e. The charge purge supply and exhaust connections at the charge are TBD.

3.1.2.2 Process Data Interface

- a. The temperature-time profile of the reaction process will be provided by B&W, and will be entered at the control system keyboard in a format TBD. The data set will also include events and control levels such as vacuum or partial pressure and gas temperature.
- b. Process log data from the equipment control system shall be provided at both RS232 and RS422 output jacks. Output shall be comma-delimited ASCII unless otherwise approved.

3.1.2.3 Facility Interface

- a. The layout of the equipment shall be determined by the equipment supplier. The control console shall be convenient to the chamber door. Facility area required shall be minimized.
- b. The facility is serviced by an overhead crane with 15-ton capacity and a 25-ft hook height. Standard web slings for lifting the equipment, tooling, and coils will be provided by B&W. Any special lifting or handling devices required for equipment installation or operation shall be part of the coil reaction equipment.
- c. Electrical power will be provided by the facility at 60 Hz, 115 vac single phase; 240 vac three phase; and 480 vac three phase. Power requirements shall be specified by the equipment supplier. Cabling to wall connections, and switchgear at the equipment, shall be part of the equipment.
- d. Shop air will be provided by the facility at 72 to 130 psig. The flow rate and connection shall be specified by the equipment supplier. Tubing to the facility connections, and valving and regulators at the equipment, shall be part of the equipment.
- e. Makeup cooling water will be provided by the facility at a temperature between 4 and 35°C (39 and 95°F). The flow rate and connection shall be specified by the equipment supplier. The equipment shall provide for recirculation and water

conditioning. Piping to the facility connections and valving at the equipment shall be part of the equipment. The cooling tower will be mounted on a concrete pad outside the building and fully exposed to the elements.

- f. Argon and helium inert gases will be supplied at a pressure up to 30 psig on CGA 580 male fittings. The purity of the gas supplies will be TBD. Tubing to the supply manifold connections, valving and regulators at the equipment, and exhaust stacks shall be part of the equipment. The supply tanks will be located outside the building and fully exposed to the elements.

3.1.3 Process Description

- a. The furnace charge will be determined by coil production considerations. A thermal model of the charge will be analyzed by B&W before the charge is assembled to determine a configuration of heaters and baffles that will ensure temperature uniformity. Necessary fixture modifications will be fabricated by B&W. The reaction process control program will be established based on the type of superconductor and results of the thermal analysis.
- b. The coil(s) is transferred by crane from the winding station to the reaction equipment transfer cart. Thermocouples, internal heater banks, and the conductor purge manifold and exhaust are installed. The charge is loaded into the furnace, and connections are made to the power, signal, and purge gas feed-throughs.
- c. Helium is flowed through the conductor to purge it of contaminants. The furnace is evacuated and the system is checked for leaks. Heat may be applied to accelerate outgassing of the conductor, until the oxygen concentration in both the purge exhaust and the chamber is less than 0.1 ppm.
- d. When the required oxygen concentration is reached, the reaction cycle is begun. Various types of superconductor require different reaction temperature-time profiles. The chamber may be backfilled with a partial pressure of argon to accelerate heating by convective heat transfer up to a temperature of 350°C.
- e. Above 350°C, vacuum is re-established and the cycle continued. A typical reaction cycle lasts 20 days.
- f. When the reaction cycle is completed, power is removed from the heaters and the charge begins to cool by radiant heat transfer to the chamber walls. After helium leak checking, room temperature air will be introduced to the internal cooling panels and exhausted to the outdoors. A partial pressure of argon may be re-established in the chamber to accelerate cooldown.
- g. After cool-down, the chamber is opened and the charge is removed and inspected prior to release for further processing.

3.2 Characteristics

3.2.1 Performance

3.2.1.1 Vacuum/Partial Pressure Furnace

- a. The furnace shall have a maximum leak rate of 10^{-5} torr liter/sec under any operating condition. Dual seals with intermediate vacuum pumping shall be provided on the entry door and feed-through ports.
- b. The furnace shall be capable of operating indefinitely at any temperature up to 700°C in vacuum conditions. The furnace shall be capable of continuing operation at this temperature after the failure of any one major heating system component.
- c. The furnace shall be capable of operating indefinitely at a temperature of 350°C with a partial pressure of argon or argon with up to 2% hydrogen up to 1×10^2 Pa. The furnace shall be capable of continuing operation at this temperature after the failure of any one major heating system component.

3.2.1.2 Vacuum System

- a. The vacuum system shall be capable of evacuating the furnace (without charge) to a level of 5×10^{-4} Pa (3.8×10^{-6} torr) within three hours, after the furnace door has been open to the atmosphere for at least 24 hours. Capabilities for both automatic and manual switching between roughing and high vacuum shall be provided.
- b. With the furnace at any temperature within its operating range, the vacuum system shall be capable of maintaining a vacuum of 5×10^{-4} Pa indefinitely in the event of a mechanical or electrical failure of any one major vacuum system component. Valving off of a failed vacuum system shall be automatic.
- c. No backstreaming of oil or other contaminants from the vacuum system is permissible under any normal or fault condition. No contamination of a clean witness sample shall be detectable by visual examination or by swabbing with a clean cloth after a reaction process cycle.
- d. The vacuum system shall be capable of operation with a chamber atmosphere of argon or argon with up to 2% hydrogen at a pressure of 2×10^2 Pa (1.5 torr).

3.2.1.3 Partial Pressurization System

- a. The system shall automatically maintain a programmed pressure within the furnace at any level from 1 Pa to 2×10^2 Pa, with a flow of argon or argon with up to 2% hydrogen. The gas flow rate shall not exceed 0.25 l/sec (std). Argon and hydrogen will be premixed at the supply.
- b. The system shall purify the supply of inert gas so that neither the oxygen content nor the water content exceed 0.1 ppm. A capability shall be provided to monitor the gas inlet contamination with sensitivity adequate to detect this level.

3.2.1.4 Charge Purge System

- a. The system shall automatically maintain a programmed pressure within the charge at any level between 1×10^2 Pa and 2×10^5 Pa, with a flow of helium or helium with up to 2% hydrogen. The gas flow rate shall not exceed 10 l/sec (std). Helium/hydrogen will be premixed at the supply.
- b. The system shall purify the supply of gas so that neither the oxygen content nor the water content exceed 0.1 ppm. A capability shall be provided to monitor the gas inlet contamination with sensitivity adequate to detect this level.
- c. With the internal connections of the charge purge system shunted, no detectable helium shall enter the furnace atmosphere at any flow rate up to 10 l/sec (std) and any pressure up to 2×10^5 Pa.
- d. The system shall contain valving to enable the charge to be evacuated from the furnace vacuum plenum.

3.2.1.5 Heater System

- a. The heater system shall be capable of achieving a programmed steady-state temperature, as measured on the surface of the charge, within the range 100 to 700°C, with a total error not to exceed $\pm 5^\circ\text{C}$. The total error includes control errors and non-uniformities due to the heater zone configuration relative to the charge.
- b. The heater system shall be capable of achieving the following programmable temperature rates of change measured at the surface of any specified charge:

<i>Condition</i>	<i>Temp. Range</i>	<i>Rate of Change</i>
Heat-up in argon	27 to 350°C	6 to 55 °C/hr
Heat-up in vacuum	220 to 675°C	6 to 75 °C/hr

The total temperature error shall not exceed $\pm 15^\circ\text{C}$ during transients, including control errors and non-uniformities due to the heater zone configuration relative to the charge.

- c. The control system shall be capable of detecting a fault in any charge-mounted thermocouple, and initiating an alarm to cause operator switch-over to a redundant thermocouple.

3.2.1.6 Chamber Wall Cooling System

- a. Water cooling circuits shall be provided on the chamber walls to satisfy the safety requirements of 3.3.6.c.
- b. The water jacket in the chamber walls shall prevent condensation within the furnace at any time.
- c. The water cooling system shall be equipped to prevent clogging by particulates, and shall be protected from corrosion throughout the coolant loops.

3.2.1.7 Internal Cooling System

- a. Air-cooled panels shall be provided facing the charge within the chamber. The air flow shall be capable of producing the following temperature rates of change measured at the surface of any specified charge:

<i>Condition</i>	<i>Temp. Range</i>	<i>Rate of Change</i>
Cool-down in vacuum	675 to 300°C	12 to 30 °C/hr
Cool-down in argon	350° to 90°C	12 to 30 °C/hr

- b. The air circuit within the chamber shall have provision for flooding with helium and leak checking through the chamber vacuum-system before the introduction of air. The leak rate shall not exceed 10^{-5} torr l/sec.
- c. The air circuit shall be connected by valving to the chamber vacuum system so that the circuit can be evacuated when not in use for cooling or leak checking. The valving shall permit isolation and evacuation of the internal air circuit if contamination is detected by the chamber RGA during operation.

3.2.1.8 Control System

- a. The control system shall be based on a computer and/or programmable controller. The system shall have diagnostic capabilities to detect and identify fault conditions in any equipment subsystem. It shall have data output capability (both to a CRT and to a disc for retention as a historical record) to permit manual control, performance verification, and debugging of the control program and furnace hardware.
- b. The control console shall be ergonomically designed. The operator control interface shall be intelligible to a generally skilled laborer with a minimum of training.
- c. The following minimum parameters shall be programmable in the process data set:
1. Three temperature ramp rates for heat-up
 2. Two temperature ramp rates for cool-down
 3. Temperature hold points
 4. Activation/deactivation of partial pressurization system
 5. Activation/deactivation of purge system
 6. Pressure level for partial pressurization system
 7. Pressure level for purge system
 8. Activation/deactivation of heat exchanger system
- d. The following parameters shall be under closed-loop control. If any parameter is not within program limits, an alarm shall be initiated and the control algorithm shall initiate a safing action (such as heater zone disabling, valve closure, or furnace pressurization with argon) to limit the temperature excursion or contamination of the charge. A warning shall be issued prior to the alarm, where practicable.
1. Charge temperature level
 2. Charge temperature rate of change
 3. Chamber vacuum or partial pressure
 4. Purge system vacuum or partial pressure
 5. Coolant temperature

- e. The following parameters shall be monitored by the system. If any parameter is not within program limits, an alarm shall be initiated and the control algorithm shall initiate a safing action (such as valve closure) to limit contamination of the charge. A warning shall be issued prior to the alarm, where practicable.
 - 1. Argon contamination level at furnace pressurization inlet
 - 2. Helium contamination level at the purge system inlet.
- f. The following minimum controls shall be available to the operator at the control console:
 - 1. Manual or automatic run selection
 - 2. Program designation
 - 3. Vacuum system auto initiation
 - 4. Leak check switch and readout
 - 5. Program interrupt
 - 6. Manual temperature set
 - 7. Alarm indications and resets
- g. The following minimum capabilities shall be available to a supervisor, identified by password, at the control console:
 - 1. Control program loading and modification
 - 2. Manual override of furnace temperature control parameters
 - 3. Manual override of purge and partial pressure programmed levels
 - 4. Any other function needed to tune program execution.
- h. Data displayed at the control console shall be in engineering units, and shall include all parameters listed in subparagraphs c, d, and e above plus any other parameters needed to verify proper operation, such as inert gas supply pressure, water temperature, etc. Alarms requiring operator response shall be both audible and visible.
- i. The system shall limit access to control functions to operators and supervisors identified by valid passwords. The identity of operators and supervisors on the system, and their times of log-on and log-off, shall be recorded.
- j. The system shall automatically boot up into the manual mode on power up.

3.2.1.9 Data Logging System

- a. The data logging system shall record header information prior to the initiation of a furnace run which shall include:
 - 1. Run identity
 - 2. Operator identity
 - 3. Date and time
 - 4. Charge identity.
- b. The data logging system shall record an initial leak rate at the initiation of a heating cycle.
- c. The data logging system shall record temperature from up to 36 charge-mounted thermocouples at intervals not to exceed 5 minutes.

- d. The data logging system shall record the chamber vacuum level and RGA readings at intervals not to exceed 5 minutes when in the vacuum mode and the temperature is above 90°C.
- e. When in the partial pressure mode, the data logging system shall record the following at intervals not to exceed 5 minutes:
 - 1. Partial pressure
 - 2. Argon flow rate
 - 3. Contaminant levels in the gas feed.
- f. When the charge purge system is in use and the charge temperature is in excess of 90°C, the data logging system shall record the following at intervals not to exceed 5 minutes:
 - 1. Pressure on the feed side
 - 2. Flow rate
 - 3. Contaminant levels on the inlet and outlet sides.
- g. The output data shall include the nature of all alarms and other remarkable occurrences. All data shall be tagged by date and time.

3.2.1.10 Backup Power Supply System.

- a. In the event of facility power disruption, the control system, data logging system, vacuum system, pressurization systems, and all other essential subsystems except heating and cooling, shall be powered by a backup power supply for at least 30 minutes.
- b. No process control parameters shall exceed their allowable limits as a result of power disruption and switching to the backup source.

3.2.1.11 Operating Cycles and Useful Life

- a. The equipment shall have a useful life consistent with processing no less than 28 coils, with the following quantity by type, in a period of three years:

TF	17
PF-1	3
PF-2	2
PF-3	2
PF-4	2
PF-5	2

3.2.2 Physical Characteristics

- a. The minimum furnace hot zone size shall be 20 ft x 12 ft x 10 ft high.
- b. Work platforms shall be provided within the chamber that enable safe access for electrical and gas connections on the charge and at the chamber feed-throughs.

3.2.3 Reliability

- a. The equipment design shall be evaluated to determine potential failure modes, and shall incorporate provisions to ensure a high probability of successfully completing a reaction cycle.
- b. The equipment design shall ensure that no single component failure during a reaction cycle will cause damage to the charge, including but not limited to a temperature excursion outside specified limits or oxygen contamination of the charge.
- c. The equipment design shall include fail-safe features to limit damage in the event of an equipment failure, including but not limited to overlapping heater zones, over-temperature detectors and zone cutoffs, gas line shutoff valves, and a capability to flood the chamber with an inert gas in case of a vacuum leak.

3.2.4 Maintainability

- a. All components subject to periodic preventive maintenance or expected repair within the life expectancy shall be designed for ease of access without excessive disassembly of the equipment. Components critical to cycle reliability shall be located outside the chamber, to the extent possible.
- b. The equipment shall be designed such that preventive maintenance is not required more frequently than once every ten complete coil reaction cycles. Elapsed time for preventative maintenance shall not exceed 8 hours.
- c. The mean corrective maintenance time shall not exceed 12 hours.

3.2.5 Environmental Conditions

- a. Equipment installed indoors shall be designed for use in a shop environment with temperatures varying from 10 to 35°C (50 to 95°F), and relative humidity of 10 to 95%.
- b. Equipment installed outdoors shall be designed to withstand a temperature range of -30 to 55°C (-20 to 130°F); relative humidity of 10 to 100% with precipitation in the form of rain, snow, or ice; and wind up to 100 MPH.

3.3 Design and Construction.

3.3.1 Materials, Processes, and Parts

- a. All parts and materials used in the construction of the equipment shall be suitable for the intended function. Used and reconditioned parts and assemblies may be incorporated into the equipment, provided performance and reliability are not compromised.
- b. Programmable controllers integrated into the control system shall be Allen-Bradley manufacture, and computers shall be Ziotech manufacture unless otherwise approved.
- c. External non-contact surfaces shall be either a corrosion resistant material or shall be sand blasted and painted with a two-component epoxy paint.

- d. Contact surfaces shall be either corrosion resistant or treated with an adherent conversion coating to prevent corrosion.
- e. Hydraulic systems shall be designed and constructed in accordance with the National Fluid Power Association. Hydraulic Fluid Power Systems Standard for Stationary Industrial Machinery. T2.24.1.
- f. The design of the furnace shall minimize virtual leaks and constrictions that would limit vacuum pumping efficiency.

3.3.2 *Electromagnetic Compatibility*

The equipment shall be designed for use in a shop environment which includes the operation of heavy-duty electric motors and electric arc welders, as well as sensitive computers and control electronics. The equipment shall not be susceptible to radiated or conducted electromagnetic interference typical of such an environment, nor shall it create interference greater than levels typical of such other equipment.

3.3.3 *Nameplates and Product Marking*

- a. An identification plate shall be affixed to the side of the winding machine listing the name "TPX Coil Reaction Furnace", the number of this specification and revision, the manufacturer and manufacturer's identification number, the procurement entity and contract number, a tool identification number to be furnished by B&W, the date of manufacture, and any other relevant information.
- b. All major unit subassemblies shall be permanently identified by the unit descriptor, part number, serial number, supplier, and month and year of manufacture. Replaceable components shall be clearly marked with identifiers traceable to the circuit schematics, parts lists, and other documentation used for maintenance.
- c. Internal wiring shall be identified by wire number traceable to the circuit schematics and wiring diagrams used for maintenance. Terminal blocks shall be provided with markings corresponding to those of the wire and wiring diagrams.

3.3.4 *Workmanship*

- a. The equipment shall be fabricated and assembled in a workmanlike manner, and shall be accurate in dimensions and alignment of parts with respect to the tolerances on the design drawings. The equipment shall be free of burrs and sharp edges.
- b. Assemblies and parts thereof shall be cleaned of smudges; loose, spattered or excess solder; weld metal; metal chips and mold release agents; or any other foreign material which might detract from the intended operation, function or appearance.
- c. Screws, nuts and bolts shall show no evidence of cross threading, mutilation, or detrimental or hazardous burrs, and shall be firmly secured. Fastener installation shall conform to the specified type and tightness or torquing.
- d. Wires and cables shall be positioned or protected to avoid contact with rough or irregular surfaces and sharp edges to avoid damage to insulation, conductors, or adjacent parts.

- e. Shielding on wires and cables shall be secured in a manner to prevent contact or shorting of exposed current-carrying parts. The ends of shielding or braid shall be secured to prevent fraying.
- f. Harnesses and cable containment shall be neat in appearance, uniformly applied and positioned to retain critical form factors and breakout locations. The containment means shall not cause the wire or cable insulation to deform so that performance characteristics are adversely affected.
- g. There shall be no evidence of burns, abrading or pinch marks in the insulation that could cause short circuits or current leakage.
- h. The machine shall be free of oil, water, and gas leaks, either in service or when idle.

3.3.5 *Interchangeability of Components*

Design tolerances shall permit parts and assemblies of the same part number to be used as replacement items without detracting from the specified performance of the parent item.

3.3.6 *Safety*

- a. The design of the equipment shall comply with the Occupational Safety and Health Standards, CFR 29, Chapter XVII, Part 1910; the National Electrical Code; and the National Fire Protection Association Standard for Industrial Furnaces Using Special Processing Atmosphere, NFPA 86C-91, Class D.
- b. The equipment design shall minimize hazards to personnel and product. Where the equipment design cannot eliminate hazardous equipment, processes or materials, suitable safety markings and/or procedures shall be posted on the equipment.
- c. Protective guards shall be provided to prevent shock, burns or entanglement in the equipment by operators. Power and control cabling shall be routed to avoid interference with operators. External surface temperatures shall not exceed 30°C (86°F). Interlocks or safety markings shall be provided where removal of protective features could expose personnel to hazards.
- d. Vacuum system and purge system exhausts shall be external to the building housing the equipment. High temperature exhaust shall be elevated or guarded to avoid personnel hazard.
- e. The furnace shall be equipped with emergency stop/vent switches inside the vacuum chamber.

3.3.7 *Human Factors*

- a. The design of the equipment shall be consistent with human capabilities to operate and maintain the equipment in an efficient and safe manner, in accordance with good commercial practice.
- b. Controls and indicators shall be located and configured to minimize the probability of human error in operation.

- c. Access to maintainable components, and provisions for removal and replacement thereof, shall permit accurate, efficient and safe maintenance of the equipment.

3.4 Documentation

3.4.1 Drawings

- a. Certified foundation and installation drawings shall be prepared, showing the location and sizes of all services, an outline of the floor area required to clear all equipment motions, total net weight, and major individual component weights. Drawings shall also show bolt layout and the purpose of each bolt, isolation requirements, and maximum allowable weights on work piece-mounting interfaces.
- b. As-built equipment drawings shall be prepared for delivery in accordance with good commercial practice to describe the system installation and interconnections. The drawings shall include a scaled plan view, front elevation, and end elevation, and shall contain major equipment dimensions and work clearances. The drawings shall also include hydraulic, pneumatic, and electrical schematics and routing diagrams adequate for design and construction of facilities, and for installation and maintenance of the system.
- c. Electrical wiring and schematic diagrams shall be prepared in accordance with the following Joint Industries Conference standards:
 - 1. Electrical Standards for Mass Production Equipment, EMP.1.1967
 - 2. Electronic Standards for Mass Production Equipment and General Purpose Machine Tools, EL-1-71
- d. All drawings shall be prepared using Computer Aided Design methods, and shall be furnished in three hard copy sets and in an electronic format compatible with Intergraph or IGES format. Dimensioning and tolerancing shall be in accordance with ANSI Y-14.5M. Drawings shall be prepared with consistent metric or English units; dual dimensioning is permitted, but if used the metric units shall be shown in parentheses.

3.4.2 Operation and Maintenance Manuals

- a. Technical manuals shall be prepared to describe equipment operation and maintenance functions. The manuals shall enable manufacturing personnel with technical skills to independently operate and maintain the equipment with minimal specialized training. Control functions shall be clearly documented in the operating manual and in a help function readily accessible from the control panel. Safety requirements shall also be detailed in the operating manual.
- b. The manuals shall contain or shall reference wiring diagrams and schematics; mechanical layouts; parts lists; and operating, diagnostic, and repair procedures. The manuals shall contain copies of OEM manuals for items incorporated into the equipment for which such manuals are furnished.

3.4.3 Software

- a. Software furnished for equipment control shall be documented with functional descriptions, block diagrams, data item descriptions, and source code listings and compilers for special applications. Special applications shall be written in Microsoft C++ or Allen Bradley Ladder Logic.
- b. Standard operating system and application software shall be furnished with OEM manuals and site licenses for use at B&W's facility. The latest available version of standard software at the time of equipment delivery shall be furnished with the equipment.
- c. Initial data loads shall be documented and furnished with the equipment.

4. QUALITY ASSURANCE PROVISIONS

4.1 General

4.1.1 *Responsibility for Tests and Inspections*

The equipment supplier is responsible for verification and demonstration of compliance with all requirements of this specification. The supplier may use his own facilities or any other laboratory acceptable to the buyer for performance of required tests and demonstrations. B&W reserves the right to witness any tests and demonstrations performed by supplier, or to perform any inspection, test, or demonstration necessary to assure that the equipment conforms to the specified requirements.

4.1.2 *Special Verifications*

- a. Supplier shall prepare and deliver documentation, including analyses and demonstration records that verify conformance to requirements inherently determined by the design of the equipment.
- b. Final verification and acceptance of the equipment shall be based on a full functional demonstration of compliance with the Verification Matrix after equipment installation at B&W's facility. The capability to detect and properly respond to fault conditions and power interrupts shall be demonstrated.

4.1.3 *Quality Assurance System*

Supplier shall provide documentation of conformance to the requirements specified herein, prepared within a system that assures the integrity of the data furnished. The system shall include provisions for inspection, maintenance of test and measuring equipment, control of non-conforming material, and record-keeping in accordance with B&W QT 9403, Quality Requirements.

4.2 Quality Conformance Matrix

Verification of the requirements of this specification shall be in accordance with the Quality Conformance Matrix, Table 4-1. The indicated methods of verification are defined as follows:

- a. Analysis: verification by calculation or simulation, including computer modeling based on established material or component characteristics.
- b. Demonstration: observation of functional operation at ambient; or review of design drawings and specifications; or review of data for similar components and applications.
- c. Inspection: measurements of dimensions, time, electrical parameters, etc., performed at ambient with general-purpose instruments; or review of records from prior conformance verification.
- d. Test: verification by physically exercising a component or system under appropriate loads and operating conditions, including measurement and analysis of performance data.

Table 4-1
TPX Coil Reaction Equipment Quality Conformance Matrix

<i>Paragraph</i>	<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>	<i>N/A</i>
3.1 Item Definition					x
3.1.1 Item Diagram		x			
3.1.2 Interface Definition					x
3.1.2.1 Charge Interfaces		x			
3.1.2.2 Process Data Interface		x			
3.1.2.3 Facility Interfaces		x			
3.1.3 Process Description					x
3.2 Characteristics					x
3.2.1 Performance					x
3.2.1.1 Vacuum/Partial Pressure Furnace		x		x	
3.2.1.2 Vacuum System		x		x	
3.2.1.3 Partial Pressurization System		x		x	
3.2.1.4 Charge Purge System		x		x	
3.2.1.5 Heater System	x	x		x	
3.2.1.6 Chamber Wall Cooling System		x		x	
3.2.1.7 Internal Cooling System	x	x		x	
3.2.1.8 Control System		x		x	
3.2.1.9 Data Logging System		x		x	
3.2.1.10 Backup Power Supply		x		x	
3.2.1.11 Operating Cycles and Useful Life		x			
3.2.2 Physical Characteristics					x
3.2.3 Reliability		x			
3.2.4 Maintainability		x			
3.2.5 Environmental Conditions		x			
3.3 Design and Construction					x
3.3.1 Materials, Processes, and Parts		x			
3.3.2 Electromagnetic Compatibility		x			
3.3.3 Nameplates and Product Marking			x		
3.3.4 Workmanship			x		
3.3.5 Interchangeability of Components		x			
3.3.6 Safety		x			
3.3.7 Human Factors		x			
3.4 Documentation					x
3.4.1 Drawings		x			
3.4.2 Manuals		x			
3.4.3 Software		x			

5. PREPARATION FOR DELIVERY

The equipment shall be delivered in place at the coil manufacturer's facility.

6. NOTES

10. APPENDIX

10.1 Charge Drawings

Figure 10-1 Charge Configuration, TF Coil

TOP VIEW

(UPPER STRONGBACK OMITTED FOR CLARITY)

END VIEW

COIL TYPE	DIM. "X"	DIM. "Y"	WEIGHT (LBS.)	WEIGHT (Kg.)
PF1	18.8"	105"	6820	3100
PF2	15"	101"	5940	2700
PF3	9.4"	95"	4620	2100
PF4	9.4"	95"	4620	2100

Figure 10-2 Charge Configuration, PF 1-4 Coil

TOP VIEW

(Upper Strongback Plate Omitted for Clarity)

END VIEW

Estimated Weight of
Coil and Tooling is
9700 lbs(4400 Kg.)

Figure 10-3 Charge Configuration, PF-5 Coil

PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**TPX COIL VPI
EQUIPMENT SPECIFICATION**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-SPEC-133-0004
REVISION 0**

Prepared for: the University of California
Lawrence Livermore National Laboratory
Subcontract B235308, SDRL 20

Prepared by: the Babcock & Wilcox Company
NNFD, Accelerator and Magnet Systems
Mt. Athos Road, Lynchburg, VA 24505

The original document is on file at B&W.

It was prepared and signed by:	R.R. Batchelder, B&W Systems Engineering
It was approved and signed by:	R.F. Ryan, B&W TPX Manufacturing Engineer
It was approved and signed by:	C.M. Weber, B&W TPX Project Manager
It was approved and signed by:	E.W. Southwick, LLNL QA Engineer
It was approved and signed by:	G.A. Deis, LLNL Magnet WBS Manager

SIGNATURE SHEET

Prepared by:
R.R. Batchelder, B&W Systems Engineering

Approved by:
R.F. Ryan, B&W TPX Mfg. Engineer

Approved by:
C.M. Weber, B&W TPX Project Manager

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G.A. Deis, LLNL Magnet WBS Manager

DOCUMENT CHANGE RECORD

<i>SCN No.</i>	<i>Change Description</i>	<i>Rev</i>	<i>Date</i>
	Initial issue		

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1. SCOPE

This document specifies the performance, design, documentation, and quality assurance requirements for Vacuum Pressure Impregnation (VPI) Equipment for use in the manufacture of superconducting magnet coils for the Tokamak Physics eXperiment (TPX). Eight types of coil will be manufactured with the equipment.

The VPI Equipment will be installed at a single manufacturing facility for all coils. A single mixing chamber, control system, and cable set will be provided for all mold types.

The VPI equipment will be furnished complete and integrated at the manufacturing facility. The system will include an as-built drawing set and manuals describing system operation and maintenance.

The TPX coils are high-value items, and are extremely fragile when undergoing the VPI process. The design and construction of the equipment shall provide for safe and reliable coil handling and processing, as well as for safety of personnel, consistent with economy of construction and efficiency of operation.

2. APPLICABLE DOCUMENTS

The following documents of exact issue shown shall apply to the extent referenced herein. In the event of conflict between the provisions of any of the listed documents and this specification, the provisions of this specification shall prevail.

1. Occupational Safety and Health Standards, CFR 29, Chapter XVII, Part 1910
2. Joint Industries Conference, Electrical Standards for Mass Production Equipment, EMP.1.1967
3. Joint Industries Conference, Electronic Standards for Mass Production Equipment and General Purpose Machine Tools, EL-1-71
4. National Electrical Code
5. ASME Boiler and Pressure Vessel Code, Section VIII
6. B&W Quality Requirements, QT 9403
7. Dimensioning and Tolerancing, ANSI Y14.5M-1982

3. REQUIREMENTS

3.1 Item Definition

3.1.1 Item Diagram

The VPI Equipment shall include the following major elements, as shown in Figure 3-1:

- a. Vacuum- and pressure-tight, heated VPI molds that contain the coils during epoxy impregnation and pressure curing. The VPI molds shall be portable, and shall be supported by stands that allow connection of manifolds on the underside of the molds. A vacuum system shall be provided for evacuation of any mold. The molds shall be covered with thermal insulation blankets for temperature uniformity, efficiency, and personnel safety.
- b. A vacuum- and pressure-tight chamber and motorized agitator for de-gassing and mixing the components of the epoxy used to impregnate the coils. The chamber shall be elevated for drainage, and heated to control the viscosity of the compound. A vacuum system shall be provided for evacuation of the chamber.
- c. Heated piping and manifolds that feed the epoxy components to the mixing chamber and the mixed epoxy to the coil mold. Tubing shall also be provided from a facility dry nitrogen supply to the mixing chamber and coil mold.
- d. A control and data logging system that initiates process operations from a single point, controls the mixing and curing temperatures, and that the records and displays data from the process.
- e. Cables and wiring that connect the various system elements and that connect to facility power.

3.1.2 Interface Definition

3.1.2.1 Coil Interface

- a. The approximate sizes and shapes of the TPX coils that shall be contained in the VPI molds are provided in Figures 10-1 to 10-8. Final coil sizes, corresponding to the inside dimensions of the VPI molds, will be provided at a later date.
- b. Each coil contains a pair of leads that must penetrate the VPI molds; and tubular stubs that will be sealed before VPI operations. The VPI Equipment shall contain seals to permit evacuation and pressurization of the mold, and to prevent epoxy from flowing along the leads or stubs. Structural support and protection shall be provided for the leads extending from the mold, as part of the mold.

3.1.2.2 Facility Interfaces

- a. The layout of VPI equipment shall be determined by the equipment supplier. The control console shall be convenient to the epoxy mixing chamber and epoxy feed valves. Facility area required shall be minimized.
- b. The facility is serviced by an overhead crane with 15-ton capacity and a 25-ft hook height. Standard web slings for lifting the VPI mold or coils will be provided by the coil manufacturer. Any required special lifting or handling devices shall be part of the VPI equipment.

VPI MOLD

PLASTIC TUBING AND MANIFOLD
FOR EPOXY FLOW DISTRIBUTION

Figure 3-1 VPI Equipment Diagram

- c. Electrical power will be provided by the facility at 60 Hz, 110-, 220-, and 460-vac. Power requirements shall be specified by the equipment supplier. Cabling to wall connections, and switchgear at the equipment, shall be part of the VPI equipment.
- d. Dry nitrogen will be provided by the facility at 100 psig. The flow rate and connection shall be specified by the equipment supplier. Tubing to the facility connections, and valving and regulators at the equipment, shall be part of the VPI equipment.
- e. The epoxy for coil impregnation will be provided by the coil manufacturer, and will be either a two-part or three-part compound. Supply containers and stands are part of the facility. Tubing to the supply containers, with associated valving, is part of the VPI equipment.

3.1.2.2 Process Data Interface

- a. Control levels and events, including temperature, vacuum, and pressure settings and valve actuations will be input at the control system keyboard in a format TBD.
- b. Process log data from the equipment control system shall be provided at both RS232 and RS422 output jacks. Output shall be comma-delimited ASCII unless otherwise approved.

3.1.3 Process Description

3.1.3.1 Process Preparation

- a. The coil will be placed in the assembled VPI mold at a location other than the VPI station, and will be moved to the VPI station by overhead crane. The coil is comprised of metal conductor wrapped with polyimide film and dry glass-fiber cloth. The inside of the VPI mold will have been sprayed with a mold release agent before the coil is placed within.
- b. The coil and mold are placed on the VPI station stand, and seals are installed around the coil leads and stubs. The mold cover will be installed, and epoxy manifold connections will be made. Electrical connections will be made to the mold for heater power and instrumentation. Vacuum and dry nitrogen pressure connections are made.
- c. Vacuum and pressure leak tightness of the mold and the empty epoxy mixing container are checked. Proper functioning of the control system is verified. Thermal insulation blankets are placed around the mold.

3.1.3.2 Coil and Epoxy De-gassing

- a. The valve at the inlet of the epoxy supply pipe, and the pressurization valves are closed.
- b. The VPI mold is evacuated; the vacuum level is monitored, and pumping continued until a suitable, stable vacuum level is reached. Heat will be applied to the mold to accelerate out-gassing and to bring the coil to the proper temperature for impregnation.
- c. The epoxy mixing container is evacuated, and epoxy resin is introduced from the supply at ambient air pressure. Agitation is begun, and the evolution of bubbles and

the vacuum level are monitored until a suitable, stable vacuum level is reached. Heat will be applied to reduce the viscosity of the epoxy resin.

3.1.3.3 Vacuum Pressure Impregnation

- a. The accelerator or catalyst is metered into the epoxy mixing container, and the compound is mixed. When mixing and de-gassing are complete, the mixing container vacuum valve is closed and the container is pressurized with facility dry nitrogen.
- b. The valve at the inlet to the epoxy supply pipe is opened, and epoxy is allowed to flow under pressure into the evacuated VPI mold from the bottom. The appearance of epoxy at a uniform level in the overflow columns indicates that the mold is filled, at which point the supply pipe and vacuum manifold valves are closed.
- c. Pressure is applied to the liquid epoxy from the facility dry nitrogen supply, and the temperature of the mold is raised to the proper curing temperature. Pressure will normally be applied for approximately one hour. The curing cycle will take 40 to 60 hours at ambient pressure with intermediate temperature changes, depending on the epoxy type.
- d. After filling of the VPI mold, epoxy remaining in the mixing container is dumped, the feed pipe is removed, and the container and feed pipe are cleaned for re-use.

3.1.3.4 Coil Removal and Cleanup

- a. Following coil impregnation and curing, power is removed from heaters and the VPI mold and coil cool to shop ambient temperature.
- b. The insulation blankets are removed, and the mold is dis-assembled for removal of the processed coil. The inlet manifolds and overflow columns contain hardened epoxy, and will be sawed off for removal from the mold. Portions of the mold surrounding the coil leads and stubs will be separated at their seals.
- c. Either at the VPI station, or at a separate station, the coil will be manually cleaned-up by removal of hardened epoxy remaining outside the end-product envelope, removal of seals, and smoothing of mold marks.

3.2 Characteristics

3.2.1 Performance

3.2.1.1 Vacuum Level

- a. The vacuum system for the VPI mold shall achieve and sustain a vacuum level of 10^{-3} Torr after pumping for no more than 30 minutes on the empty and sealed mold.
- b. The vacuum system for the epoxy mixing container shall achieve and sustain a vacuum level of 10^{-4} Torr after pumping for no more than 10 minutes on the empty and closed container.
- b. Both vacuum systems shall be configured to prevent backstreaming of oil or any other contaminant into the VPI mold or mixing chamber under any condition.

3.2.1.2 Impregnation Time

- a. The system shall be capable of epoxy mixing, final de-gassing, and impregnating any coil within an epoxy pot life period of no more than four (4) hours.
- b. The epoxy resin shall be de-gassed before introduction of the hardener or catalyst; final mixing begins when the final component is added to the resin.

3.2.1.3 Curing Temperature and Pressure

- a. Heaters on the VPI mold shall provide a curing temperature that is controllable within the range 100 to 160°C. The temperature measured at any point on any VPI mold type shall be within $\pm 5^\circ\text{C}$ of the setpoint after stabilization.
- b. The rate of temperature increase of any VPI mold type shall be not less than 20°C per hour.
- c. Pressure shall be applied from the facility dry nitrogen supply to the liquid epoxy during curing. The pressure shall be regulated by the VPI equipment, up to the facility supply pressure of 100 psig.

3.2.1.4 Controls and Data Logging

- a. The VPI equipment shall include sensors, a programmable logic controller (PLC), software, and peripheral equipment to perform the functions described herein. The system shall be operable by a single technician at a computer video display terminal with keyboard.
- b. The system shall continuously monitor and display key process parameters including vacuum and pressure levels and temperatures in the VPI mold and epoxy mixing container, and valve and switch positions. Audible and visible alarms shall be activated in the event that key parameter ranges are exceeded, including loss of vacuum, epoxy flow stoppage, and over-temperature.
- c. The system shall automatically control the temperature in the VPI mold and epoxy mixing container in accordance with setpoint programs input at the terminal.
- d. The system shall contain an internal clock for sequencing function changes; it shall display elapsed process time; and it shall tag and store all sensed process parameters for plotting as time profiles. Profile plots shall be available with operator-selectable parameters and scales, in real time and delayed, and on-screen and printed. A continuous time-tagged listing of operator control actions shall also be available.
- e. The controller and critical components shall be powered with an uninterruptible power supply that is part of the VPI equipment, such that loss of facility power for a period up to 30 minutes will not cause loss of a coil or loss of process data.

3.2.1.5 Operating Cycles and Useful Life

The system shall have a useful life consistent with processing no less than 32 coils, with the following quantity by type, in a period of three years:

TF	17
PF-1	3
PF-2	2
PF-3	2
PF-4	2
PF-5	2
PF-6	2
PF-7	2

3.2.2 *Physical Characteristics*

3.2.2.1 VPI Molds and Manifolds

- a. The sizes of the VPI molds for the different coil types shall be as specified in 3.1.2.1. Coil types PF-1 through PF-4 have the same diameters, and shall use the same base and cover hardware with cylindrical sections designed to the different heights of the coils.
- b. A manifold shall be provided beneath the VPI mold to distribute epoxy from the feed pipe upward to the interior of the mold. The manifold for each coil type shall be designed to achieve uniform distribution of epoxy and complete impregnation of the coils. The manifolds will be discarded and replaced after processing each coil.
- c. Each VPI mold shall contain transparent overflow columns to permit visual observation of the level of epoxy fill in the mold. The overflow columns will be discarded and replaced after processing each coil. The mold vacuum and pressurization manifolds shall connect to the tops of the overflow columns.
- d. Each VPI mold shall be designed for safe and efficient disassembly following coil processing. Removal of the mold, particularly in the region of the coil leads and stubs, shall not subject the coil or leads to mechanical shock or strain. Provisions shall be made for parting the manifold and overflow column connections, and for attaching lift slings to the coil, without prying, shocking, or straining the coil.

3.2.2.2 Epoxy Mixing Container

- a. The epoxy mixing container shall have a capacity of not less than 120 U.S. gal. The ratio of diameter to height of liquid shall be not less than 1:3.
- b. The epoxy feed pipe from the container to the VPI mold shall have vacuum- and pressure-tight valves at each end. The inlet valve shall be of the proportional type and shall be electrically operated from the controller; the outlet valve shall be manually operated and will be disposable. An epoxy flow sensor shall be provided in the pipe.
- c. The container and the feed pipe shall be constructed of smooth stainless steel, easily accessible and compatible with solvent cleaning. A valve shall be provided in the bottom of the container for draining the contents of the container. The pipe shall be detachable from the container and VPI mold for cleaning.
- d. The container shall have a window in its top enabling visual observation of the entire liquid surface for the evolution of bubbles during degassing. The interior of the container shall be illuminated from the top.

- e. The container shall have a mechanical agitator capable of accelerating de-gassing and mixing the liquid contents in vacuum.
- f. The container shall be heated, with the wall temperature controllable within the range 50 to 100°C. The temperature measured at any point in contact with the liquid shall be within $\pm 5^\circ\text{C}$ of the setpoint after stabilization.
- g. The container shall include tubing and valving to control the filling of the container from at least three epoxy component supply containers.
- h. The container shall contain a fitting, valve, and regulator connecting to the facility dry nitrogen supply for pressurization up to 100 psig.

3.2.3 Reliability

- a. The VPI equipment shall be designed for reliable operation in the specified operating life. Once the flow of epoxy to the coil has started, no single component failure within the VPI equipment shall cause failure to complete filling the VPI mold.

3.2.4 Maintainability

- a. The VPI equipment shall be designed for ease of maintenance. The controller shall contain self-test provisions that enable verification of all critical functions at the start of a process run. Replaceable components shall be placed and installed for ease of access and repair.
- b. The VPI equipment shall not require preventive maintenance more frequently than once every ten complete process cycles or once per year, whichever is shorter. The elapsed time for preventive maintenance shall not exceed eight hours.

3.2.5 Environmental Conditions

- a. The VPI equipment shall be designed for use in a shop environment with ambient temperature in the range 10 to 35°C (50 to 95°F), and relative humidity of 10 to 95%.

3.3 Design and Construction

3.3.1 Materials, Processes, and Parts

- a. All parts and materials used in the construction of the VPI equipment shall be suitable for the intended function. Used and reconditioned parts and assemblies may be incorporated into the equipment, provided performance and reliability are not compromised.
- b. Pressurized components of the VPI equipment shall be designed and constructed in accordance with the ASME Boiler and Pressure Vessel Code.
- c. The PLC shall be Allen Bradley unless otherwise approved.

3.3.2 Electromagnetic Compatibility

The VPI equipment shall be designed for use in a shop environment which includes the operation of heavy-duty electric motors and electric arc welders, as well as sensitive computers and control electronics. The VPI equipment shall not be

susceptible to radiated or conducted electromagnetic interference typical of such an environment, nor shall it create interference greater than levels typical of such other equipment.

3.3.3 Nameplates and Product Marking

- a. All unit assemblies shall be permanently identified by a nameplate containing the unit descriptor, part number, serial number, supplier, and month and year of manufacture.
- b. Replaceable components shall be clearly marked with identifiers traceable to the circuit schematics, parts lists, and other documentation used for maintenance.
- c. Internal wiring shall be identified by wire number traceable to the circuit schematics and wiring diagrams used for maintenance. Terminal blocks shall be provided with markings corresponding to those of the wire and wiring diagrams.

3.3.4 Workmanship

- a. The VPI equipment shall be fabricated and assembled in a workmanlike manner, and shall be accurate in dimensions and alignment of parts with respect to the tolerances on the design drawings. The equipment shall be free of burrs and sharp edges.
- b. Assemblies and parts thereof shall be cleaned of smudges; loose, spattered or excess solder; weld metal; metal chips and mold release agents; or any other foreign material which might detract from the intended operation, function or appearance.
- c. Screws, nuts and bolts shall show no evidence of cross threading, mutilation, or detrimental or hazardous burrs, and shall be firmly secured. Fastener installation shall conform to the specified type and tightness or torquing.
- d. Wires and cables shall be positioned or protected to avoid contact with rough or irregular surfaces and sharp edges to avoid damage to insulation, conductors, or adjacent parts.
- e. Shielding on wires and cables shall be secured in a manner to prevent contact or shorting of exposed current-carrying parts. The ends of shielding or braid shall be secured to prevent fraying.
- f. Harnesses and cable containment shall be neat in appearance, uniformly applied and positioned to retain critical form factors and breakout locations. The containment means shall not cause the wire or cable insulation to deform so that performance characteristics are adversely affected.
- g. There shall be no evidence of burns, abrading or pinch marks in the insulation that could cause short circuits or current leakage.

3.3.5 Interchangeability of Components

Design tolerances shall permit parts and assemblies of the same part number to be used as replacement items without detracting from the specified performance of the parent item.

3.3.6 Safety

- a. The design of the VPI equipment shall comply with the following codes and standards:
 1. Occupational Safety and Health Standards, CFR 29, Chapter XVII, Part 1910
 2. National Electrical Code
- b. The equipment design shall minimize hazards to personnel and product. Protective guards shall be provided to prevent personnel access to high voltages and temperatures. External surface temperatures shall not exceed 40°C (130°F). Interlocks or safety markings shall be provided where removal of protective features could expose personnel to hazards.
- c. The system shall be designed to fail safe. No temperature or pressure excursions in excess of rated limits shall occur as a result of power loss or any upset condition.

3.3.7 Human Factors

- a. The design of the VPI equipment shall be consistent with human capabilities to operate and maintain the equipment in an efficient and safe manner, in accordance with good commercial practice.
- b. Controls and indicators shall be located and configured to minimize the probability of human error in operation.
- c. Access to maintainable components, and provisions for removal and replacement thereof, shall permit accurate, efficient and safe maintenance of the equipment.

3.4 Documentation

3.4.1 Drawings

- a. As-built equipment drawings shall be prepared for delivery in accordance with good commercial practice to describe the system installation and interconnections. Such drawings shall include unit layouts, schematics, and wiring diagrams adequate for design and construction of facilities, and for installation and maintenance of the system.
- b. Electrical wiring and schematic diagrams shall be prepared in accordance with the following Joint Industries Conference standards:
 1. Electrical Standards for Mass Production Equipment, EMP.1.1967
 2. Electronic Standards for Mass Production Equipment and General Purpose Machine Tools, EL-1-71
- c. All drawings shall be prepared using Computer Aided Design methods, and shall be furnished in three hard copy sets and in an electronic format compatible with Intergraph or IGES format. Dimensioning and tolerancing shall be in accordance with ANSI Y-14.5M. Drawings shall be prepared with consistent metric or English units; dual dimensioning is permitted, but if used the metric units shall be shown in parentheses.

3.4.2 Operation and Maintenance Manuals

- a. Technical manuals shall be prepared to describe VPI equipment operation and maintenance functions. The manuals shall enable coil manufacturing personnel with technical skills to independently operate and maintain the equipment with minimal specialized training. The manuals shall contain or shall reference wiring diagrams and schematics; mechanical layouts; parts lists; and operating, diagnostic, and repair procedures.
- b. The manuals shall contain copies of OEM manuals for items incorporated into the VPI equipment for which such manuals are furnished.

3.4.3 Software

- a. Software furnished for equipment control shall be documented with functional descriptions, block diagrams, data item descriptions, and source code listings and compilers for special applications. Special applications shall be written in Allen Bradley Ladder Logic.
- b. Standard operating system and application software shall be furnished with OEM manuals and site licenses for use at the coil manufacturer's facility. The latest available version of standard software at the time of equipment delivery shall be furnished with the equipment.
- c. Initial data loads shall be documented and furnished with the equipment.

4. QUALITY ASSURANCE PROVISIONS

4.1 General

4.1.1 Responsibility for Tests and Inspections

The VPI equipment supplier is responsible for verification and demonstration of compliance with all requirements of this specification. The supplier may use his own facilities or any other laboratory acceptable to the buyer for performance of required tests and demonstrations. The buyer reserves the right to witness any tests and demonstrations performed by supplier, or to perform any inspection, test, or demonstration necessary to assure that the equipment conforms to the specified requirements.

4.1.2 Special Verifications

- a. Supplier shall prepare and deliver documentation, including analyses and demonstration records that verify conformance to requirements inherently determined by the design of the equipment.
- b. Final verification and acceptance of the equipment shall be based on processing of a mockup coil (a complete coil fabricated with copper cable in place of superconductor) after equipment installation at the coil manufacturer's facility.

4.1.3 Quality Assurance System

Supplier shall provide documentation of conformance to the requirements specified herein, prepared within a system that assures the integrity of the data furnished. The system shall include provisions for inspection, maintenance of test and measuring equipment, control of non-conforming material, and record-keeping in accordance with B&W QT 9403, Quality Requirements.

4.2 Quality Conformance Matrix

Verification of the requirements of this specification shall be in accordance with the Quality Conformance Matrix, Table 4-1. The indicated methods of verification are defined as follows:

- a. Analysis: verification by calculation or simulation, including computer modeling based on established material or component characteristics.
- b. Demonstration: observation of functional operation at ambient; or review of design drawings and specifications; or review of data for similar components and applications.
- c. Inspection: measurements of dimensions, time, electrical parameters, etc., performed at ambient with general-purpose instruments; or review of records from prior conformance verification.
- d. Test: verification by physically exercising a component or system under appropriate loads and operating conditions, including measurement and analysis of performance data.

Table 4-1
TPX Coil VPI Equipment Quality Conformance Matrix

<i>Paragraph</i>	<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>	<i>N/A</i>
3.1 Item Definition					X
3.1.1 Item Diagram		X			
3.1.2 Interface Definition					X
3.1.2.1 Coil Interface		X			
3.1.2.2 Facility Interfaces		X			
3.1.2.3 Process Data Interface		X			
3.1.3 Process Description					X
3.1.3.1 Process Preparation					X
3.1.3.2 Coil and Epoxy De-gassing					X
3.1.3.3 Vacuum Pressure Impregnation					X
3.1.3.4 Coil Removal and Cleanup					X
3.2 Characteristics					X
3.2.1 Performance					X
3.2.1.1 Vacuum Level		X		X	
3.2.1.2 Impregnation Time		X		X	
3.2.1.3 Curing Temperature and Pressure		X		X	
3.2.1.4 Controls and Data Logging		X		X	
3.2.1.5 Operating Cycles and Useful Life		X			
3.2.2 Physical Characteristics					X
3.2.2.1 VPI Molds and Manifolds		X			
3.2.2.2 Epoxy Mixing Container		X			
3.2.3 Reliability		X			
3.2.4 Maintainability		X			
3.2.5 Environmental Conditions		X			
3.3 Design and Construction					X
3.3.1 Materials, Processes, and Parts		X			
3.3.2 Electromagnetic Compatibility		X			
3.3.3 Nameplates and Product Marking			X		
3.3.4 Workmanship			X		
3.3.5 Interchangeability of Components		X			
3.3.6 Safety		X			
3.3.7 Human Factors		X			
3.4 Documentation					X
3.4.1 Drawings		X			
3.4.2 Operation and Maintenance Manuals		X			
3.4.3 Software		X			

5. PREPARATION FOR DELIVERY

The VPI equipment shall be delivered in place at the coil manufacturer's facility.

6. NOTES

10. APPENDIX

10.1 Coil Drawings

Coil Designation	Figure #	Weight (lbs)
TF	10-1	16,654
PF-1	10-2	6,820
PF-2	10-2	5,940
PF-3	10-2	4,620
PF-4	10-2	4,620
PF-5	10-3	9,700
PF-6*		
PF-7*		

* Coils PF-6 and -7 will be impregnated in their cases; no VPI mold is required. For reference, the outside diameter of PF-6 is 307.40 in., and of PF-7 is 349.87 in.

Figure 10-1 TF Coil

COIL TYPE	DIM. "X"	DIM. "Y"
PF1	18.8"	105"
PF2	15"	101"
PF3	9.4"	95"
PF4	9.4"	95"

TOP VIEW

END VIEW

Figure 10-2 PF-1 - PF-4 Coils

Figure 10-3 PF-5 Coil