TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE

Contract B235308

SDRL 21

Materials & Processes Selection

August 18, 1995

13-950811-BW-RSmith-04

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PRELIMINARY

**TF Magnet
Materials and Processes
Selection Report
(SDRL 21)**

TOKAMAK PHYSICS EXPERIMENT

Date: August 15, 1995

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1.0 SCOPE

This document identifies the candidate materials and manufacturing processes selected for development of the TPX Toroidal Field (TF) Magnet. Supporting rationale and selection criteria are provided for justification and the material properties database report is included for completeness. Specific properties for each material selection are included in this document.

2.0 APPLICABLE DOCUMENTS

2.1 TPX Program Documents

2.1.1 TPX-STND-005/94-950615-PPPL-IZatz-02: TPX Material Properties Handbook

2.2 Specifications and Standards

2.2.1 Handbook on Materials for Superconducting Machinery, Metals and Ceramics
Information Center, January 1977

(Note: Specific material property references are listed in Appendix A: TF Magnet Materials Database Report)

2.3 Contractor Documents

2.3.1 13-950727-BW-PRackov-03: TF Coil Reaction Procedure

2.3.2 13-950524-BW-HBell-01: TF Coil Winding Procedure

2.3.3 13-950727-BW-NAIbritton-02: TF Coil Cleaning, Insulation and Vacuum Pressure Impregnation Procedure

2.3.4 13-950727-BW-HBell-01: TF Case Assembly Procedure

2.3.5 14-12210.3-WSTC/JFRoach-M12-06-05-95: "Revision of Mechanical Properties Matrix of Insulation Materials for Structural/Thermal Analyses"/TPX Material Property Database

2.3.6 13-950818-BW-RBatchelder-01: TF Magnet System Design Description

2.3.7 SDRL 34: TF Magnet Material and Component Testing Plan

3.0 TF MAGNET MATERIALS AND PROCESSES DATABASE

In order to document the selection of materials and processes and the corresponding selection criteria and rationale for the TF Magnet, the TF Magnet Materials and Processes Database was developed. This database is configured to support the following activity:

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- to facilitate the addition or deletion of selected materials and corresponding properties and selection criteria and rationale
- to allow the assignment of candidate materials to individual TF Magnet components
- to provide TF Magnet parts list information including hierarchy designations and part numbers
- to store manufacturing process data including process selection criteria and rationale, process conditions, and special cautions
- to provide a method of organizing all materials and process data into customized reports.

4.0 SELECTION APPROACH

4.1 Materials Selection

Candidate materials selection for the TF Magnet components has developed as an iterative process involving design analysis and material performance investigation. A large portion of the TF Magnet is comprised of stainless steel which has been listed in the TPX Material Properties Handbook (reference 2.1.1). Insulation material properties were extracted from the TPX Material Property Table developed by Westinghouse and MIT (reference 2.3.5). All TF materials (including weld filler materials), corresponding properties, selection criteria and rationale are listed in Appendix A. Materials and corresponding properties that are not currently listed in the TPX Material Properties Handbook have been provided to the TPX Materials Committee for review, verification, and incorporation into the program handbook.

4.1.1 Material Properties Data

A section of the TF Magnet Materials and Processes database was developed for storage of material properties data, selection criteria and rationale, and material properties data sources. A listing of the material property and selection information can be found in Appendix A. In general, material selection for individual components was based on material characteristics such as magnetic permeability, material strength and stiffness, thermal conductivity, or electrical insulation capability. Material properties were researched through standard handbooks, existing material specifications, and vendor-provided data sheets. As the TF Magnet design matures, the material data will be updated to maintain program consistency and completeness.

4.1.2 Component Material Assignment

The TF parts and materials section of the database provides the capability for a material to be assigned to each component of the TF Magnet system. The parts list present in the database is based on the TF Octant portion of the magnet as shown in Drawing 4.1.2-1. A listing of the TF Magnet parts and corresponding material assignments can be found in Appendix B. To reduce the parts and materials database report length, subassemblies have been excluded and only individual parts listed.

4.2 Processes Data

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The other section of the Materials and Processes Database was developed to store information pertaining to the TF Magnet manufacturing processes. The major manufacturing processes included in the database are the following:

- TF Coil Winding
- TF Coil Cleaning, Insulation and Vacuum Pressure Impregnation
- TF Coil Reaction
- TF Case Assembly
- TF Welding

Brief descriptions, selection criteria and rationale, and manufacturing procedure references are provided for each of the major processes are provided in Appendix C: TF Processes Report. Special cautions and process conditions for each process are also noted.

5.0 VERIFICATION

5.1 Materials Verification

TF Magnet materials verification will be accomplished through material and component testing. Special material testing that is needed to support existing data or to determine specific material properties has been identified in the TF Magnet Material and Component Testing Plan (reference 2.3.7). Additional data is being obtained through the insulation materials research and development activity being performed by Westinghouse Corporation. Information regarding materials for isolators, flowmeters, etc. is to be provided by LLNL and/or MIT.

5.2 Process Verification

TF Magnet manufacturing process verification will be accomplished through testing and research and development activities. Information regarding TF Magnet process verification can be found in the TF Magnet SDD (reference 2.3.6).

NOTES:

1. BRACKETS ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED SHALL BE FROM FRONT VIEW.
2. MATERIALS:
3. MARK PART NUMBER & SERIAL NUMBER FOR IDENTIFICATION.

SECTION A-A

PRELIMINARY

DATE: 6-7-93 TIME: 10:00 A.M.

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

CONTRACT NO. B235308

DATE: 6-7-93

TIME: 10:00 A.M.

TF OCTANT ASSEMBLY

BABCOCK & WILCOX

LYNCHBURG, VIRGINIA 23060

SCALE: 1"=1'-0"

SHEET: 1

DRAWING 4.1.2-1

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Appendix A

TF Magnet Material Properties Report

TF Material Selection and Properties Report

Material ID: 12
Material Designation: Aluminum, Crepe Foil
Criteria: EM shielding,, material strength, flexibility for winding pack ground plane insulation

Rationale: EM shielding, material flexibility, good tensile strength

Special/Additional Testing:

Material Data Source: Avery Dennison/Framingham, MA: Electrical Insulation & Shielding Materials/Insulflex Crepe Foil--Data Sheet

Material Properties **Temp:** RT
Density: **Thickness:** .019" unstretched **Dielectric Strength:**
Thermal Conductivity: **Spec. Heat:**
Other Properties: Tensile Strength=15 lbs. (min.); Yield Strength=approx. 4 psi; Elongation=60% (min.)

Material ID: 17
Material Designation: Bronze
Criteria: Source material for the Sn necessary to form Nb3Sn

Rationale: Source material for the Sn necessary to form Nb3Sn

Special/Additional Testing:

Material Data Source: Ref. LLNL Conductor Specification TBD

Material Properties **Temp:**
Density: **Thickness:** **Dielectric Strength:**
Thermal Conductivity: **Spec. Heat:**
Other Properties:

Material ID: 20
Material Designation: Copper, bar, OFHC, Annealed
Criteria: Electrical conductivity for splice usage

Rationale: Electrical conductivity

Special/Additional Testing:

Material Data Source: 'Handbook on Materials for Superconducting Machinery', January 1977; Spec. CDA No. 102

Material Properties **Temp:** 77 K
Density: **Thickness:** **Dielectric Strength:**
Thermal Conductivity: **Spec. Heat:**
Other Properties: Tensile Ultimate Strength=360 MN/m²; Tensile Yield Strength=88.2 MN/m² (avg); elongation=60.1%

TF Material Selection and Properties Report

Material ID: 13
Material Designation: Copper, Sheet, OFHC, Annealed
Criteria: Thermal conductivity for reaction process spacer material

Rationale: Thermal conductivity; flexibility

Special/Additional Testing:

Material Data Source: 'Handbook on Materials for Superconducting Machinery', January 1977; Spec. CDA No. 102

Material Properties

Temp: 77 K

Density: .8933 lb/in³

Thickness: .064 in.

**Dielectric
Strength:**

Thermal Conductivity:

Spec. Heat:

Other Properties: Yield Strength=16 ksi; Ultimate Tensile Strength=56 ksi

Material ID: 8

Material Designation: Copper, strand, pure, Type 10100, OFHC or equivalent, Cr plated

Criteria: 0.78 mm diameter, 1 micrometer Cr plating, half-hard temper

Rationale: See criteria

Special/Additional Testing:

Material Data Source: "Preliminary Parts List", J. Zbasnik, LLNL, 7/3/95

Material Properties

Temp: RT - 4K

Density:

Thickness:

**Dielectric
Strength:**

Thermal Conductivity:

Spec. Heat:

Other Properties:

Material ID: 23

Material Designation: Copper, Tube, TBD

Criteria: CTE, thermal conductivity

Rationale: CTE, thermal conductivity

Special/Additional Testing:

Material Data Source: See properties for Copper, Sheet

Material Properties

Temp:

Density:

Thickness:

**Dielectric
Strength:**

Thermal Conductivity:

Spec. Heat:

Other Properties:

TF Material Selection and Properties Report

Material ID: 9

Material Designation: Epoxy, Shell EPON 826

Criteria: Shear strength, electrical insulation capabilities, bond strength

Rationale: Shear strength, electrical insulation capabilities, bond strength

Special/Additional Testing:

Material Data Source: Material Ref: Program memo dated 6/05/95, Frank Roach; EPON Resin 826, Shell Resins Technical Data Sheet, SC:235-94.826

Material Properties

Temp: 4 K

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties: Low viscosity

Material ID: 26

Material Designation: Epoxy, Shell EPON Resin 1007F

Criteria: High performance tackifier for insulation preform

Rationale: See Criteria; selection listed in "Winding Pack Design and Analysis 3D Weave Development" presentation by WEC at May TIM #5

Special/Additional Testing:

Material Data Source: EPON Resin 1007F Technical Bulletin, Shell Chemical Company, SC:235-87.107F

Material Properties

Temp: RT

Density: 36-40 lb/ft³

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

Material ID: 27

Material Designation: G10, Block, 2D Weave

Criteria: Dielectric strength and insulation capabilities for spacers

Rationale: Dielectric strength and insulation capabilities

Special/Additional Testing:

Material Data Source: See G10, Sheet data

Material Properties

Temp:

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

TF Material Selection and Properties Report

Material ID: 10
Material Designation: G10, Sheet, 2D Weave
Criteria: Insulation capabilities; dielectric strength.

Rationale: Insulation capabilities; dielectric strength.

Special/Additional Testing:

Material Data Source: Program memo dated 6/05/95, Frank Roach

Material Properties

Temp: 4 K

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

Material ID: 14
Material Designation: Incoloy 908, Tube, Annealed

Criteria: Compatibility with CTE of Nb3Sn, material strength, fracture toughness, high-temperature stability during lengthy reaction process.

Rationale: CTE compatibility with Nb3Sn, strength, fracture toughness, high-temperature stability during lengthy reaction process.

Special/Additional Testing:

Material Data Source: Program memo dated 6/05/95, Frank Roach; 1314-950226-MIT/JSchultz-01: "Comparison of Incoloy 908 with 316LN for TPX Conduits

Material Properties

Temp: 4 K

Density: 8110 kg/m³

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties: Yield Stress=1300 MPa; Tensile Strength=1800 MPa

Material ID: 4
Material Designation: Inconel, Filler Metal 625

Criteria: Resistance to cracking; low weld shrinkage, high strength; low magnetic permeability

Rationale: Resistance to cracking; approximately 1/3 weld distortion of 316LN; high strength and ductility; low magnetic permeability

Special/Additional Testing: Qualification test for welding SS 316LN

Material Data Source: Inco Alloys International data sheet

Material Properties

Temp: RT

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties: Tensile Strength=120-150 ksi; Yield Strength=60-110 ksi; elongation=60-30 %; Fatigue Strength=58-68 ksi

TF Material Selection and Properties Report

Material ID: 19
Material Designation: Polyimide (Kapton), Tape, Type 100 HN
Criteria: Dielectric strength; slip plane for insulation.

Rationale: Dielectric strength.

Special/Additional Testing:

Material Data Source: Program memo dated 6/05/95, Frank Roach

Material Properties

Temp: 4 K

Density:	Thickness:	Dielectric
Thermal Conductivity:	Spec. Heat:	Strength:
Other Properties:		

Material ID: 21
Material Designation: S-2 Glass, 3D Weave, Preform
Criteria: CTE match with incoloy 908; high strength; near uniform cross-sectional properties

Rationale: CTE match with incoloy 908; high strength; near uniform cross-sectional properties

Special/Additional Testing:

Material Data Source: Program memo dated 6/05/95, Frank Roach

Material Properties

Temp: 4 K

Density:	Thickness:	Dielectric
Thermal Conductivity:	Spec. Heat:	Strength:
Other Properties:		

Material ID: 11
Material Designation: S-2 Glass, Tape, 3D Weave
Criteria: Material stiffness and strength, CTE match with Incoloy 908; through-thickness strength

Rationale: Material stiffness and strength, CTE match with Incoloy 908; through-thickness strength

Special/Additional Testing:

Material Data Source: Program memo dated 6/05/95, Frank Roach

Material Properties

Temp: 4 K

Density:	Thickness: .014	Dielectric
Thermal Conductivity:	Spec. Heat:	Strength:
Other Properties:		

TF Material Selection and Properties Report

Material ID: 24
Material Designation: SS, 316LN, standard part
Criteria: Standard bolts, screws, etc.

Rationale:

Special/Additional Testing:

Material Data Source:

Material Properties

Temp:

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

Material ID: 22
Material Designation: SS, Block, 316LN
Criteria: Low magnetic permeability, strength

Rationale: Low magnetic permeability, strength

Special/Additional Testing:

Material Data Source: See TPX Material Properties Handbook for specific properties

Material Properties

Temp:

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

Material ID: 5
Material Designation: SS, Forged, 316LN, annealed
Criteria: Low magnetic permeability, strength; uniform material properties

Rationale: Low magnetic permeability, strength; uniform material properties

Special/Additional Testing:

Material Data Source: See TPX Material Properties Handbook for specific properties

Material Properties

Temp: RT - 4K

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

TF Material Selection and Properties Report

Material ID: 3
Material Designation: SS, Plate, 316LN, annealed
Criteria: Low magnetic permeability, strength

Rationale: Low magnetic permeability, strength

Special/Additional Testing:

Material Data Source: See TPX Material Properties Handbook for specific properties

Material Properties

Temp: 4 K

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

Material ID: 7
Material Designation: SS, Thick walled seamless tube, 316LN, Drawn
Criteria: Material strength under pressure; fracture toughness

Rationale: Material strength under pressure; fracture toughness; material compatability with coil case

Special/Additional Testing:

Material Data Source:

Material Properties

Temp: RT - 4K

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

Material ID: 1
Material Designation: Subassembly
Criteria:

Rationale:

Special/Additional Testing:

Material Data Source:

Material Properties

Temp:

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength:

Other Properties:

TF Material Selection and Properties Report

Material ID: 25

Material Designation: Ultem 2300

Criteria: Bolt material to withstand radiation environment; dielectric strength

Rationale: Radiation environment performance; dielectric strength

Special/Additional Testing:

Material Data Source: "Ultem Polyetherimide Resin Material Guide", General Electric; "A Low Cost Support Post for SSC Quadrupole Magnets and Other Cryogenic Applications", B&W, July 12-16, 1993

Material Properties

Temp: RT

Density:

Thickness:

Dielectric

Thermal Conductivity:

Spec. Heat:

Strength: 769 V/mil (

Other Properties: Tensile Strength, yield= 24500 psi; Shear Strength, ultimate=14000 psi

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Appendix B

TF Magnet Parts/Materials Report

TPX TF Magnet Parts and Materials Report

Database ID:	1	BOM Level:	3		
Part Number:	133-6480	Quantity:	2	Material ID:	24
Part Name:	1/4 Hex Nut				
Material Type/Form:	SS, 316LN, standard part				
Database ID:	2	BOM Level:	3		
Part Number:	133-6481	Quantity:	42	Material ID:	24
Part Name:	1/4 Lock Washer				
Material Type/Form:	SS, 316LN, standard part				
Database ID:	3	BOM Level:	3		
Part Number:	133-6479	Quantity:	2	Material ID:	24
Part Name:	1/4 x 1 Hex Bolt				
Material Type/Form:	SS, 316LN, standard part				
Database ID:	4	BOM Level:	3		
Part Number:	133-6484	Quantity:	49	Material ID:	24
Part Name:	1/4 x 1.25 Hex Bolt				
Material Type/Form:	SS, 316LN, standard part				
Database ID:	5	BOM Level:	3		
Part Number:	133-6477	Quantity:	12	Material ID:	25
Part Name:	3/8 x 3 Soc Hd Cap Screw				
Material Type/Form:	Ultem 2300				
Database ID:	6	BOM Level:	2		
Part Number:	133-5202	Quantity:	2	Material ID:	21
Part Name:	3D S2 Glass Woven Preform				
Material Type/Form:	S-2 Glass, 3D Weave, Preform				
Database ID:	7	BOM Level:	2		
Part Number:	133-5201	Quantity:	2	Material ID:	11
Part Name:	3D S2 Glass Woven Tape 0.014				
Material Type/Form:	S-2 Glass, Tape, 3D Weave				
Database ID:	8	BOM Level:	2		
Part Number:	133-5204	Quantity:	2	Material ID:	11
Part Name:	3D S2 Glass Woven Tape 0.024				
Material Type/Form:	S-2 Glass, Tape, 3D Weave				
Database ID:	9	BOM Level:	2		
Part Number:	1334203	Quantity:	28	Material ID:	10
Part Name:	Alignment Pad				
Material Type/Form:	G10, Sheet, 2D Weave				

TPX TF Magnet Parts and Materials Report

Database ID:	10	BOM Level:	2		
Part Number:	133-5205	Quantity:	2	Material ID:	12
Part Name:	Aluminum Crepe				
Material Type/Form:	Aluminum, Crepe Foil				
Database ID:	11	BOM Level:	4		
Part Number:	133-4248	Quantity:	2	Material ID:	3
Part Name:	Bearing Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	12	BOM Level:	2		
Part Number:	133-4150	Quantity:	1	Material ID:	3
Part Name:	Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	13	BOM Level:	2		
Part Number:	133-4151	Quantity:	1	Material ID:	3
Part Name:	Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	14	BOM Level:	2		
Part Number:	133-4151	Quantity:	1	Material ID:	3
Part Name:	Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	15	BOM Level:	2		
Part Number:	133-4150	Quantity:	1	Material ID:	3
Part Name:	Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	16	BOM Level:	3		
Part Number:	1334236	Quantity:	2	Material ID:	3
Part Name:	Case Inner Shell				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	17	BOM Level:	2		
Part Number:	Outer	Quantity:	3	Material ID:	23
Part Name:	Case Loop				
Material Type/Form:	Copper, Tube, TBD				
Database ID:	18	BOM Level:	2		
Part Number:	Inner	Quantity:	3	Material ID:	23
Part Name:	Case Loop				
Material Type/Form:	Copper, Tube, TBD				

TPX TF Magnet Parts and Materials Report

Database ID:	19	BOM Level:	3		
Part Number:	1334232	Quantity:	2	Material ID:	3
Part Name:	Case Outer Shell - Port				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	20	BOM Level:	3		
Part Number:	1334230	Quantity:	2	Material ID:	3
Part Name:	Case Outer Shell - Top				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	21	BOM Level:	3		
Part Number:	1334233	Quantity:	2	Material ID:	3
Part Name:	Case Outer Shell - Upper				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	22	BOM Level:	3		
Part Number:	1334231	Quantity:	2	Material ID:	3
Part Name:	Case Outer Shell -Bottom				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	23	BOM Level:	5		
Part Number:	1334317	Quantity:	2	Material ID:	3
Part Name:	Case Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	24	BOM Level:	5		
Part Number:	1334316	Quantity:	2	Material ID:	3
Part Name:	Case Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	30	BOM Level:	3		
Part Number:	1334210	Quantity:	2	Material ID:	3
Part Name:	Coil Case Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	31	BOM Level:	2		
Part Number:	133-6485	Quantity:	1	Material ID:	3
Part Name:	Cross Bar Base Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	32	BOM Level:	2		
Part Number:	133-6488	Quantity:	1	Material ID:	3
Part Name:	Cross Brace 1				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	33	BOM Level:	2		
Part Number:	133-6489	Quantity:	1	Material ID:	3
Part Name:	Cross Brace 2				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	34	BOM Level:	2		
Part Number:	133-6490	Quantity:	1	Material ID:	3
Part Name:	Cross Brace 3				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	35	BOM Level:	2		
Part Number:	133-6491	Quantity:	1	Material ID:	3
Part Name:	Cross brace 4				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	36	BOM Level:	2		
Part Number:	133-6492	Quantity:	1	Material ID:	3
Part Name:	Cross brace 5				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	40	BOM Level:	1		
Part Number:	133-4705	Quantity:	1	Material ID:	3
Part Name:	Front Access Panel				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	41	BOM Level:	2		
Part Number:	133-6493	Quantity:	1	Material ID:	7
Part Name:	Front Support Tube				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	42	BOM Level:	3		
Part Number:	133-6403	Quantity:	6	Material ID:	3
Part Name:	Hanger Bracket Adjustable Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	43	BOM Level:	3		
Part Number:	133-6449	Quantity:	8	Material ID:	10
Part Name:	Hanger Bracket Bottom Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	44	BOM Level:	3		
Part Number:	133-6451	Quantity:	8	Material ID:	3
Part Name:	Hanger Bracket Bottom Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	45	BOM Level:	3		
Part Number:	133-6478	Quantity:	24	Material ID:	3
Part Name:	Hanger Bracket Clamp Screw				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	46	BOM Level:	3		
Part Number:	133-6448	Quantity:	6	Material ID:	10
Part Name:	Hanger Bracket Fixed Side Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	47	BOM Level:	3		
Part Number:	133-6402	Quantity:	6	Material ID:	3
Part Name:	Hanger Bracket Fixed Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	50	BOM Level:	3		
Part Number:	133-6450	Quantity:	6	Material ID:	3
Part Name:	Hanger Bracket Pad Top Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	51	BOM Level:	3		
Part Number:	133-6447	Quantity:	8	Material ID:	10
Part Name:	Hanger Bracket Sliding Side Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	52	BOM Level:	3		
Part Number:	133-6404	Quantity:	6	Material ID:	3
Part Name:	Hanger Bracket Top Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	55	BOM Level:	3		
Part Number:	133-5560	Quantity:	10	Material ID:	
Part Name:	He Stub				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	61	BOM Level:	4		
Part Number:	133-5561	Quantity:	10	Material ID:	
Part Name:	He Stub Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	63	BOM Level:	3		
Part Number:	133-6442	Quantity:	1	Material ID:	3
Part Name:	Header Tube Clamp Base				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	64	BOM Level:	3		
Part Number:	133-6443	Quantity:	1	Material ID:	3
Part Name:	Header Tube Clamp Cap				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	66	BOM Level:	3		
Part Number:	Right	Quantity:	1	Material ID:	7
Part Name:	ICS Cooling Loop				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	67	BOM Level:	3		
Part Number:	Left	Quantity:	1	Material ID:	7
Part Name:	ICS Cooling Loop				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	79	BOM Level:	4		
Part Number:	1334321	Quantity:	2	Material ID:	3
Part Name:	Inboard Leg Cap				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	80	BOM Level:	4		
Part Number:	1334320	Quantity:	2	Material ID:	3
Part Name:	Inboard Leg Cap Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	83	BOM Level:	3		
Part Number:	1334235	Quantity:	2	Material ID:	3
Part Name:	Inboard Leg Inner Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	85	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	inlettube				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	86	BOM Level:	5		
Part Number:	1334313	Quantity:	2	Material ID:	3
Part Name:	Inner Shell				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	87	BOM Level:	4		
Part Number:	1334222	Quantity:	2	Material ID:	3
Part Name:	Inner Shell				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	88	BOM Level:	2		
Part Number:	1334120	Quantity:	1	Material ID:	3
Part Name:	Inner Standoff - A				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	89	BOM Level:	2		
Part Number:	1334120	Quantity:	1	Material ID:	3
Part Name:	Inner Standoff - A				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	90	BOM Level:	2		
Part Number:	1334121	Quantity:	1	Material ID:	3
Part Name:	Inner Standoff -B				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	91	BOM Level:	2		
Part Number:	1334121	Quantity:	1	Material ID:	3
Part Name:	Inner Standoff -B				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	93	BOM Level:	4		
Part Number:	133-4263	Quantity:	1	Material ID:	3
Part Name:	Lateral Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	95	BOM Level:	1		
Part Number:	133-4710	Quantity:	1	Material ID:	3
Part Name:	Lead Box Outboard Wall (Machining)				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	97	BOM Level:	1		
Part Number:	133-4701	Quantity:	1	Material ID:	3
Part Name:	Leadbox Inboard Wall				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	98	BOM Level:	2		
Part Number:	133-4711	Quantity:	1	Material ID:	22
Part Name:	Leadbox Outboard Wall (Casting)				
Material Type/Form:	SS, Block, 316LN				
Database ID:	99	BOM Level:	1		
Part Number:	133-4702	Quantity:	1	Material ID:	3
Part Name:	Leadbox Top				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	100	BOM Level:	1		
Part Number:	133-4703	Quantity:	1	Material ID:	3
Part Name:	Left Access Panel				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	101	BOM Level:	2		
Part Number:	133-4715	Quantity:	1	Material ID:	3
Part Name:	Left Access Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	104	BOM Level:	2		
Part Number:	133-4707	Quantity:	1	Material ID:	3
Part Name:	Left Lower Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	105	BOM Level:	1		
Part Number:	133-6501	Quantity:	1	Material ID:	3
Part Name:	Left Lower Bushing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	106	BOM Level:	2		
Part Number:	1334110	Quantity:	1	Material ID:	3
Part Name:	Left Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	107	BOM Level:	2		
Part Number:	133-4706	Quantity:	1	Material ID:	3
Part Name:	Left Upper Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	108	BOM Level:	1		
Part Number:	133-6502	Quantity:	1	Material ID:	3
Part Name:	Left Upper Bushing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	109	BOM Level:	2		
Part Number:	133-4204	Quantity:	2	Material ID:	10
Part Name:	Locator Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	110	BOM Level:	3		
Part Number:	133-6417	Quantity:	2	Material ID:	3
Part Name:	Long Wall Bracket				
Material Type/Form:	SS, Plate, 316LN, annealed				

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Database ID:	112	BOM Level:	3		
Part Number:	133-6418	Quantity:	4	Material ID:	3
Part Name:	Long Wall Bracket Gusset				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	115	BOM Level:	4		
Part Number:	1334225	Quantity:	2	Material ID:	3
Part Name:	Lower Vertical Rib				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	117	BOM Level:	4		
Part Number:	1334301	Quantity:	1	Material ID:	5
Part Name:	Machined Inboard Leg Forging				
Material Type/Form:	SS, Forged, 316LN, annealed				
Database ID:	118	BOM Level:	4		
Part Number:	1334202	Quantity:	1	Material ID:	3
Part Name:	Outer Plate (Vacuum Port)				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	119	BOM Level:	5		
Part Number:	1334312	Quantity:	2	Material ID:	3
Part Name:	Outer Shell				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	120	BOM Level:	3		
Part Number:	1334212	Quantity:	1	Material ID:	3
Part Name:	Outer Shell - Lower				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	121	BOM Level:	3		
Part Number:	1334213	Quantity:	1	Material ID:	3
Part Name:	Outer Shell - Upper				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	122	BOM Level:	2		
Part Number:	1334122	Quantity:	1	Material ID:	3
Part Name:	Outer Standoff - A				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	123	BOM Level:	2		
Part Number:	1334122	Quantity:	1	Material ID:	3
Part Name:	Outer Standoff - A				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	124	BOM Level:	2		
Part Number:	1334123	Quantity:	1	Material ID:	3
Part Name:	Outer Standoff - B				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	125	BOM Level:	2		
Part Number:	1334123	Quantity:	1	Material ID:	3
Part Name:	Outer Standoff - B				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	126	BOM Level:	4		
Part Number:	133-4274	Quantity:	2	Material ID:	3
Part Name:	PF5L Lat. Gusset A				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	127	BOM Level:	4		
Part Number:	133-4275	Quantity:	2	Material ID:	3
Part Name:	PF5L Lat. Gusset B				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	128	BOM Level:	4		
Part Number:	133-4272	Quantity:	1	Material ID:	3
Part Name:	PF5L Lateral Facing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	129	BOM Level:	4		
Part Number:	133-4273	Quantity:	1	Material ID:	3
Part Name:	PF5L Lateral Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	130	BOM Level:	3		
Part Number:	133-4270	Quantity:	1	Material ID:	3
Part Name:	PF5L Lateral Support				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	131	BOM Level:	4		
Part Number:	133-4278	Quantity:	2	Material ID:	3
Part Name:	PF5L Vert. Gusset				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	132	BOM Level:	4		
Part Number:	133-4276	Quantity:	1	Material ID:	3
Part Name:	PF5L Vertical Facing				
Material Type/Form:	SS, Plate, 316LN, annealed				

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Database ID:	133	BOM Level:	4		
Part Number:	133-4277	Quantity:	1	Material ID:	3
Part Name:	PF5L Vertical Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	134	BOM Level:	3		
Part Number:	133-4271	Quantity:	1	Material ID:	3
Part Name:	PF5L Vertical Support				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	135	BOM Level:	4		
Part Number:	133-4264	Quantity:	2	Material ID:	3
Part Name:	PF5U Lat. Gusset A				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	136	BOM Level:	4		
Part Number:	133-4265	Quantity:	2	Material ID:	3
Part Name:	PF5U Lat. Gusset B				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	137	BOM Level:	4		
Part Number:	133-4262	Quantity:	1	Material ID:	3
Part Name:	PF5U Lateral Facing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	138	BOM Level:	3		
Part Number:	133-4260	Quantity:	1	Material ID:	3
Part Name:	PF5U Lateral Support				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	139	BOM Level:	4		
Part Number:	133-4268	Quantity:	2	Material ID:	3
Part Name:	PF5U Vert. Gusset				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	140	BOM Level:	4		
Part Number:	133-4266	Quantity:	1	Material ID:	3
Part Name:	PF5U Vertical Facing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	141	BOM Level:	4		
Part Number:	133-4267	Quantity:	1	Material ID:	3
Part Name:	PF5U Vertical Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	142	BOM Level:	3		
Part Number:	133-4261	Quantity:	1	Material ID:	3
Part Name:	PF5U Vertical Support				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	143	BOM Level:	4		
Part Number:	133-4241	Quantity:	4	Material ID:	3
Part Name:	PF6 Vertical Facing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	144	BOM Level:	4		
Part Number:	133-4243	Quantity:	8	Material ID:	3
Part Name:	PF6 Vertical Gusset				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	145	BOM Level:	4		
Part Number:	133-4242	Quantity:	4	Material ID:	3
Part Name:	PF6 Vertical Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	146	BOM Level:	3		
Part Number:	133-4240	Quantity:	4	Material ID:	3
Part Name:	PF6 Vertical Support				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	147	BOM Level:	4		
Part Number:	133-4246	Quantity:	2	Material ID:	3
Part Name:	PF6L Lateral Facing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	148	BOM Level:	4		
Part Number:	133-4247	Quantity:	4	Material ID:	3
Part Name:	PF6L Lateral Gusset				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	149	BOM Level:	3		
Part Number:	133-4245	Quantity:	2	Material ID:	3
Part Name:	PF6L/TF Support				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	150	BOM Level:	2		
Part Number:	133-5200	Quantity:	2	Material ID:	19
Part Name:	Polyimide Insulation				
Material Type/Form:	Polyimide (Kapton), Tape, Type 100 HN				

TPX TF Magnet Parts and Materials Report

Database ID:	151	BOM Level:	3		
Part Number:	1334213	Quantity:	2	Material ID:	3
Part Name:	Port ICS Rib				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	152	BOM Level:	5		
Part Number:	1334314	Quantity:	1	Material ID:	3
Part Name:	Rib				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	153	BOM Level:	5		
Part Number:	1334315	Quantity:	1	Material ID:	3
Part Name:	Rib				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	154	BOM Level:	4		
Part Number:	1334224	Quantity:	1	Material ID:	3
Part Name:	Rib A				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	155	BOM Level:	4		
Part Number:	1334226	Quantity:	1	Material ID:	3
Part Name:	Rib B				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	156	BOM Level:	3		
Part Number:	1334214	Quantity:	1	Material ID:	3
Part Name:	Rib C				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	157	BOM Level:	3		
Part Number:	133-4215	Quantity:	1	Material ID:	3
Part Name:	Rib C (Lower)				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	158	BOM Level:	1		
Part Number:	133-4704	Quantity:	1	Material ID:	3
Part Name:	Right Access Panel				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	159	BOM Level:	2		
Part Number:	133-4716	Quantity:	1	Material ID:	3
Part Name:	Right Access Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	161	BOM Level:	2		
Part Number:	133-4709	Quantity:	1	Material ID:	3
Part Name:	Right Lower Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	162	BOM Level:	1		
Part Number:	133-6503	Quantity:	1	Material ID:	3
Part Name:	Right Lower Bushing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	163	BOM Level:	2		
Part Number:	133-4708	Quantity:	1	Material ID:	3
Part Name:	Right Upper Bolting Flange				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	164	BOM Level:	1		
Part Number:	133-6504	Quantity:	1	Material ID:	3
Part Name:	Right Upper Bushing				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	165	BOM Level:	3		
Part Number:	133-6412	Quantity:	3	Material ID:	3
Part Name:	Short Wall Bracket				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	167	BOM Level:	3		
Part Number:	133-6413	Quantity:	6	Material ID:	3
Part Name:	Short Wall Bracket Gusset				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	168	BOM Level:	2		
Part Number:	133-4114	Quantity:	1	Material ID:	3
Part Name:	Side Plate - Right				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	169	BOM Level:	3		
Part Number:	133-6436	Quantity:	2	Material ID:	3
Part Name:	Special Hanger Bracket Adjustable Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	171	BOM Level:	3		
Part Number:	133-6433	Quantity:	2	Material ID:	10
Part Name:	Special Hanger Bracket Fixed Side Pad				
Material Type/Form:	G10, Sheet, 2D Weave				

TPX TF Magnet Parts and Materials Report

Database ID:	172	BOM Level:	3		
Part Number:	133-6435	Quantity:	2	Material ID:	3
Part Name:	Special Hanger Bracket Fixed Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	173	BOM Level:	3		
Part Number:	133-6432	Quantity:	2	Material ID:	3
Part Name:	Special Hanger Bracket Top Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	174	BOM Level:	3		
Part Number:	133-6434	Quantity:	2	Material ID:	10
Part Name:	Special Hanger Bracket Top Spacer Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	175	BOM Level:	2		
Part Number:	133-6486	Quantity:	6	Material ID:	3
Part Name:	Special Hanger Bracket Vertical Adjustment Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	178	BOM Level:	3		
Part Number:	133-6422	Quantity:	2	Material ID:	3
Part Name:	Splice Bracket Adjustable Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	179	BOM Level:	3		
Part Number:	133-6427	Quantity:	2	Material ID:	10
Part Name:	Splice Bracket Bottom Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	180	BOM Level:	3		
Part Number:	133-6428	Quantity:	2	Material ID:	3
Part Name:	Splice Bracket Bottom Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	181	BOM Level:	3		
Part Number:	133-6426	Quantity:	2	Material ID:	10
Part Name:	Splice Bracket Fixed Side Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	182	BOM Level:	3		
Part Number:	133-6429	Quantity:	2	Material ID:	3
Part Name:	Splice Bracket Fixed Side Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID:	183	BOM Level:	3		
Part Number:	133-6425	Quantity:	2	Material ID:	10
Part Name:	Splice Bracket Sliding Side Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	184	BOM Level:	3		
Part Number:	133-6423	Quantity:	2	Material ID:	10
Part Name:	Splice Bracket Top Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	185	BOM Level:	3		
Part Number:	133-6424	Quantity:	2	Material ID:	3
Part Name:	Splice Bracket Top Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	187	BOM Level:	3		
Part Number:	133-6457	Quantity:	2	Material ID:	10
Part Name:	Spur				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	189	BOM Level:	3		
Part Number:	133-6458	Quantity:	2	Material ID:	10
Part Name:	Spur Cap				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	190	BOM Level:	3		
Part Number:	133-6459	Quantity:	2	Material ID:	10
Part Name:	Spur Cover Plate				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	191	BOM Level:	2		
Part Number:	133-6476	Quantity:	1	Material ID:	3
Part Name:	Spur Support Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	192	BOM Level:	2		
Part Number:	1334124	Quantity:	2	Material ID:	3
Part Name:	Standoff Rib				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	193	BOM Level:	2		
Part Number:	1334124	Quantity:	2	Material ID:	3
Part Name:	Standoff Rib				
Material Type/Form:	SS, Plate, 316LN, annealed				

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Database ID:	194	BOM Level:	4		
Part Number:	133-5520	Quantity:	2	Material ID:	7
Part Name:	Stub Tube A				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	195	BOM Level:	4		
Part Number:	133-5521	Quantity:	2	Material ID:	7
Part Name:	Stub Tube B				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	196	BOM Level:	4		
Part Number:	133-5522	Quantity:	2	Material ID:	7
Part Name:	Stub Tube C				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	197	BOM Level:	4		
Part Number:	133-5523	Quantity:	2	Material ID:	7
Part Name:	Stub Tube D				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	198	BOM Level:	4		
Part Number:	133-5524	Quantity:	2	Material ID:	7
Part Name:	Stub Tube E				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	199	BOM Level:	2		
Part Number:	133-6487	Quantity:	2	Material ID:	3
Part Name:	Support Bar Cap Plate				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	200	BOM Level:	2		
Part Number:	133-6483	Quantity:	1	Material ID:	3
Part Name:	Support Tube Elevation Block				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	201	BOM Level:	2		
Part Number:	133-6482	Quantity:	1	Material ID:	3
Part Name:	Support Tube Front Wall Mount				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	205	BOM Level:	2		
Part Number:	133-5250	Quantity:	2	Material ID:	13
Part Name:	TF Winding Spacer 1				
Material Type/Form:	Copper, Sheet, OFHC, Annealed				

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Database ID:	206	BOM Level:	2		
Part Number:	133-5251	Quantity:	2	Material ID:	13
Part Name:	TF Winding Spacer 2				
Material Type/Form:	Copper, Sheet, OFHC, Annealed				
Database ID:	207	BOM Level:	2		
Part Number:	133-5252	Quantity:	2	Material ID:	13
Part Name:	TF Winding Spacer 3				
Material Type/Form:	Copper, Sheet, OFHC, Annealed				
Database ID:	208	BOM Level:	2		
Part Number:	133-5253	Quantity:	2	Material ID:	13
Part Name:	TF Winding Spacer 4				
Material Type/Form:	Copper, Sheet, OFHC, Annealed				
Database ID:	209	BOM Level:	2		
Part Number:	133-5254	Quantity:	2	Material ID:	13
Part Name:	TF Winding Spacer 5				
Material Type/Form:	Copper, Sheet, OFHC, Annealed				
Database ID:	210	BOM Level:	2		
Part Number:	133-5255	Quantity:	2	Material ID:	13
Part Name:	TF Winding Spacer 6				
Material Type/Form:	Copper, Sheet, OFHC, Annealed				
Database ID:	212	BOM Level:	3		
Part Number:		Quantity:	4	Material ID:	7
Part Name:	tube(a)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	213	BOM Level:	3		
Part Number:		Quantity:	4	Material ID:	7
Part Name:	tube(b)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	214	BOM Level:	3		
Part Number:		Quantity:	2	Material ID:	7
Part Name:	tube(c)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	215	BOM Level:	3		
Part Number:		Quantity:	2	Material ID:	7
Part Name:	tube(d)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				

TPX TF Magnet Parts and Materials Report

Database ID:	216	BOM Level:	3		
Part Number:		Quantity:	6	Material ID:	7
Part Name:	tube(e)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	217	BOM Level:	3		
Part Number:		Quantity:	6	Material ID:	7
Part Name:	tube(f)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	218	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(g)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	219	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(h)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	220	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(i)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	221	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(j)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	222	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(k)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	223	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(l)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	224	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(n)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				

TPX TF Magnet Parts and Materials Report

Database ID:	225	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(o)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	226	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(p)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	227	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(q)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	228	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(r)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	229	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(s)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	230	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(t)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	231	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(u)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	232	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(v)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	233	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(w)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				

TPX TF Magnet Parts and Materials Report

Database ID:	234	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(x)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	235	BOM Level:	3		
Part Number:		Quantity:	1	Material ID:	7
Part Name:	tube(y)				
Material Type/Form:	SS, Thick walled seamless tube, 316LN, Drawn				
Database ID:	237	BOM Level:	3		
Part Number:		Quantity:	4	Material ID:	3
Part Name:	upper pf7 support bracket				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	239	BOM Level:	4		
Part Number:	1334223	Quantity:	2	Material ID:	3
Part Name:	Upper Vertical Rib				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	240	BOM Level:	3		
Part Number:	133-6469	Quantity:	1	Material ID:	10
Part Name:	Wall Bracket Cover Plate				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	241	BOM Level:	3		
Part Number:	133-6467	Quantity:	1	Material ID:	10
Part Name:	Wall Bracket Fixed Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	242	BOM Level:	3		
Part Number:	133-6468	Quantity:	1	Material ID:	10
Part Name:	Wall Bracket Sliding Pad				
Material Type/Form:	G10, Sheet, 2D Weave				
Database ID:	244	BOM Level:	2		
Part Number:	1334111	Quantity:	1	Material ID:	3
Part Name:	Wedging Face				
Material Type/Form:	SS, Plate, 316LN, annealed				
Database ID:	245	BOM Level:	2		
Part Number:	1334112	Quantity:	1	Material ID:	3
Part Name:	Wedging Face				
Material Type/Form:	SS, Plate, 316LN, annealed				

TPX TF Magnet Parts and Materials Report

Database ID: 246

BOM Level: 2

Part Number: 133-5203

Quantity: 2

Material ID: 9

Part Name: Winding Epoxy

Material Type/Form: Epoxy, Shell EPON 826

PRELIMINARY

Appendix C

TF Magnet Processes Report

TPX TF Magnet Processes Report

Process ID: 1

Process Name: TF Coil Winding

Component (s): Conductor, spacer materials

Process Description: Winding of TF conductor into D-shape using roll bender and straightener

Process Location: B&W/Lynchburg

Process Conditions: Clean room; coils to be covered during idle periods, welding, and machining

Special Cautions: Maintenance of clean environment; lint-free gloves during handling

Selection Criteria: Process to wind coil to within specified tolerances and to prepare coil for reaction process; clean environment process

Selection Rationale: Process to wind coil to within specified tolerances and to prepare coil for reaction process; methods for maintenance of clean room environment

Process Specification: 13-950524-BW-HBell-01 TF Coil Winding Procedure

Process ID: 2

Process Name: TF Case Assembly

Component (s): Conductor, TF Case

Process Description: Assembly of two insulated TF coils into TF case (octant assembly)

Process Location: B&W/Lynchburg

Process Conditions: Clean room; coils to be covered during idle periods, welding, and machining; lint-free gloves du

Special Cautions: Handling of leads that protrude from case; superconductor strand brittleness after reaction-dama

Selection Criteria: Process for careful handling of coil; proper alignment of coil in case; clean room environment; potting of coil in case

Selection Rationale: Process for careful handling of coil; proper alignment of coil in case; clean room environment; potting of coil in case

Process Specification: 13-950727-BW-HBell-01 TF Case Assembly Procedure

Process ID: 3

Process Name: TF Coil Reaction Process

Component (s): TF Coil, pressure gages, thermocouples

Process Description: Coil (with lead supports and thermocouples in place) is placed in furnace; coil is heated to predefined temps for specified time to react Sn and Nb.

Process Location: B&W/Lynchburg

Process Conditions: Clean room: coil to be covered during idle periods; lint-free gloves for handling

Special Cautions: Maintain vacuum and temperatures at specified levels

Selection Criteria: Clean room process; vacuum and temperature conditions to provide appropriate environment for reaction

Selection Rationale: Clean room process; vacuum and temperature conditions to provide appropriate environment for reaction

Process Specification: 13-950727-BW-PRackov-03 TF Coil Reaction Procedure

TOKAMAK PHYSICS EXPERIMENT (TPX)

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

Contract B235308

SDRL 22

**Critical Equipment Drawings, Specifications, and
Procurement Plans**

August 7, 1995

13-950807-BW-RRyan-01

Babcock & Wilcox
Accelerator & Magnet Systems
PO Box 785
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Lynchburg, VA 24505

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

SDRL #22

CRITICAL EQUIPMENT DRAWINGS, SPECIFICATIONS, AND PROCUREMENT PLANS

INTRODUCTION

This document is responsive to the following TF Magnet TSOW requirements:

1.3.7 Coil Winding System Design and Analysis

1.3.7.1 TF Magnet Winding System

[B&W] shall provide a preliminary equipment design, supporting analysis, and preliminary procedures to be used in winding the TF coils.

1.3.7.2 PF Magnet Winding System

[B&W] shall perform an engineering study to determine a Rough Order of Magnitude (ROM) estimate of the modifications needed to allow the TF winding system to also accommodate winding the PF coils.

1.3.8 Coil Reaction System Design and Analysis

1.3.8.1 TF Coil Reaction System

[B&W] shall provide procedures to be used and preliminary design and supporting analysis of the oven(s) and other ancillary equipment required to form the Nb₃Sn by heating to the appropriate temperature with the proper environment after the TF coil(s) have been formed. [B&W] shall ensure that the equipment specifications and procedures can provide the reaction conditions specified by the University.

1.3.8.2 PF Coil Reaction System

[B&W] shall perform an engineering study to determine an ROM estimate of the modifications needed to allow the TF coil reaction system to also be used to form the Nb₃Sn for the PF coils.

1.3.9 Coil Insulation, Impregnation, and Ground Wrap System Design and Analysis

1.3.9.1 TF System

[B&W] shall provide preliminary procedures to be used and preliminary design and supporting analysis of fixtures, chambers, ovens, and other equipment needed to insulate the reacted Nb₃Sn conductor, epoxy impregnate the winding pack, and apply the ground wrap to the TF windings.

1.3.9.2 PF System

[B&W] shall perform an engineering study to determine a ROM estimate of the scope of required modifications to the TF coil insulation, impregnation, and ground wrap system to also be used to insulate the PF coils.

Preliminary manufacturing equipment drawings and specifications, process descriptions, and procedures were submitted for the Preliminary Equipment Design Review (PEDR) on July 10, 1995. This submittal is an update of information presented at the PEDR

The TSOW (§1.1.1, item 8) requires submittal of a Preliminary Manufacturing Plan at PDR. A formal Manufacturing Plan (SDRL 38) is not required until Phase II, but preliminary data are contained in the following Phase I SDRL items:

*TF Coil Fabrication
(Wind, React, Insulate)*

*Structure Fabrication
and Magnet Assembly*

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 development plans, tooling lists, process times, staffing, 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 following are the referenced SDRL items:

- 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

The TSOW (§1.1.2) states that "...the TF PDR package may also describe any optional cost-saving features for tooling and manufacturing processes for the PF system which [B&W] wishes to propose." Further LLNL direction (letter dated June 30, 1995) states that "... [B&W] can employ its choice of tooling (baseline or optional, item-by-item) for the system it was not responsible for during PDR." Since B&W will manufacture all TPX coils at its facility in Lynchburg, VA, we have chosen the optional adaptation of our TF fabrication equipment to produce the PF coils, thus saving the costs of additional equipment and associated support. The equipment configurations for manufacture of both magnet types are as follows, and are described herein:

TF Fabrication (B&W Baseline)

TF Winding - conductor straightener, roll bender with twist compensation; "lazy arm" multi-axis takeup table.

TF Reaction - furnace capacity for two TF coils or a combination of TF and PF coils.

TF Insulation - release from winding/reaction-form tool, 3-spool wrapping device; VPI in mold without chamber; 2-step VPI process with spacers removed in second step to accommodate ground wrap.

PF Fabrication (B&W Option)

PF Winding - same equipment as used for TF winding for all PF coils, with alternate coil form tools.

PF Reaction - same equipment as used for TF reaction.

PF Insulation - same approach as used for TF insulation; VPI in mold, without chamber. PF-6 and -7 coil VPI in their respective coil cases.

This document contains the following sections:

A. Coil Winding

1. Process Description
2. Equipment Drawings
3. Preliminary Procedures
4. TF Coil Winding Movement Analysis
5. Coil Bending Accuracy Analysis
(see also SDRL 20, TPX-SPEC-133-0002, Coil Winding Equipment Specification)

B. Coil Reaction

1. Process Description
2. Equipment Drawings
3. Preliminary Procedures
(see also SDRL 20, TPX-SPEC-133-0003, Coil Reaction Equipment Specification)
(see also SDRL 37, Manufacturing Research Plans and Results, for Reaction Temperature Uniformity Analysis)

C. Coil Insulation

1. Process Description
2. Equipment Drawings
3. Preliminary Procedures
(see also SDRL 20, TPX-SPEC-133-0004, Coil VPI Equipment Specification)

D. Procurement Plans (This section is provided under separate cover, and is proprietary to B&W.)

1. Coil Winding
2. Coil Reaction
3. Coil Insulation

Section A. COIL WINDING

- A-1. Process Description
- A-2. Equipment Drawings
- A-3. Preliminary Procedures
- A-4. TF Coil Winding Movement Analysis
- A-5. Coil Bending Accuracy Analysis

A-1. COIL WINDING

1. Process Description:

For the purposes of procedure and equipment discussion we have defined the winding process as starting upon receipt of GFM conductor and concluding at the point the coil is released to the reaction process. Receipt inspection of the GFE is included, as is cleaning and preparation of the equipment and tooling. Excluded are any one-time operations such as aging the winding bobbin or insuring proper operation of the machine in a check-out mode.

Critical process parameters all relate to the ability to insure that the as-wound conductor pack fits within the design envelope after insulation and ground wrap application. A partial list of important parameters and process concerns is shown below and later discussed in terms of insuring compliance.

1. Overall "D" shape of the coil and centerline location around the "D".
2. Conductor build dimensions and the impact of kinks and twist.
3. Length of each turn.
4. Insulation thickness and integrity.
5. Spacer bonding and resultant conduit surface imperfections.
6. Reaction shrinkage of conductor.
7. Helium stub machining and welding access.
8. Lead forming prior to reaction.
9. Quantification of cold work and resultant impact on spring-back.
10. Spacer installation and heat transfer.
11. Re-spooling and rework

The concerns must be addressed in the context of the machine design and process of operation. The winding machine, is shown in plan view in the drawing section A-2 and consists of the following major parts each of which will be discussed in greater detail later:

1. Conductor payout spool
2. Straightening rollers
3. Roll-forming head
4. Winding Support table and drive system
5. Winding Form and conductor clamping
6. Length and twist measurement
7. Helium Stub Welding
8. Transition Bending
9. Control System

A general layout of the winding process is shown below. Section A-5 contains an analysis of the bending process for the TF magnets and supports the design described in the following pages. Additional detail is provided in the Winding Procedure A-3 and Winding Machine Specification contained in SDRL 20.

Forming accuracy is critical to the performance of the TPX coils. The nominal spacing of 0.062 inch between turns in the coil pack will be filled with glass-reinforced epoxy which

is an integral part of the coil pack structure. If the gap is so large that it is not filled with glass fibers, then resin-rich areas will exist that will be susceptible to cracking. Conversely, if the gap is too tight, the glass fiber tape will be compressed and may not be fully impregnated with epoxy. If the conductor is not accurately aligned in accordance with the design drawings, then stress concentrations may exist which could exceed the strength of the composite, also causing cracking.

B&W recommends a tolerance of ± 0.010 inch on the spacing between turns and layers. This tolerance will be achieved through stringent control of tolerances in conductor payout length measurement and in the roll benders, and control of variations in the conductor yield strength. The turns will be separated by spacers and clamped to the coil form to achieve the required overall coil dimensions. Section A.5 of this document provides an analysis of the sensitivity of forming accuracy to variations in payout length, formed radius, and material properties.

Coil Winding

1.1 Conductor payout spool

The conductor will arrive at B&W on a spool roughly 2.5 meters in diameter and 2 meters high, which equates to 225 turns with 53 turns per layer or 4 full layers and one partial layer. The dimensions of the spool will be worked out with the University-selected conductor supplier in Phase II. The conductor payout system will require two axis of travel; rotational and vertical. The spool will be located a sufficient distance away from the straightener to preclude significant forces being applied to the conductor by the change in radius of the conductor payout over 5 layers.

This concept minimizes potential for fatigue crack growth in the conductor sheath. It does require that a rather heavy spool be moved up and down roughly 2 meters but eliminates the need for a table to move the spool in the X and Y axis. Conductor payout will be controlled by the tractor payout drive system (or powered straightener) which will provide primary motive force for the conductor throughout the various operations. The spool drive will have a DC servo-motor drive (or equivalent) which will overcome the resistance of the drum to rotate and provide dynamic braking to insure proper tension between the tractor feed and the spool.

1.2. Straightening Rollers

The straightening roller system will consist of a bank of 5 or 7 opposed rollers.- The rollers may be powered and thus provide the tension needed to unspool the conductor although the motive force may be applied by a separate tractor drive system down stream of the straightening roller system. In that case the conductor will be pulled through the straightening rollers. The purpose of the straightening rollers is two-fold. The conductor should be straight entering the roll-former so its location is known and consistent. The second reason is to allow the rollers to introduce added cold work to the conductor thereby reducing the impact of local variation in the cold work of the conductor in its' as-spooled condition.

The straightening roller system will have two different modes of operation. The first mode will be typical straightening as described above. The second will be to act as a roll-former to roll form conductor and return it to the supply spool. This option would be used only in the case where the winding operation needed to be backed up for some reason. The primary roll-former would likewise act as a straightening system to pay off the previously roll-formed conductor from the winding form. In the sketch above, the rolls with the arrows depicted as filled would act as the roll-forming rollers when returning conductor to the spool. They would align and act similar to the other 4 rollers during normal roll-forming operations.

1.3. Roll-Bending Head

The roll-bender head is the main forming tool. It contains a total of 5 rollers. Only 1 roller is considered the main bending roller. It is a shaped roller with .005 inches of clearance between maximum conductor thickness and the inner walls of the roller. This shaped roll counters the tendency of the conductor to deform during roll-forming.

Roller 4 is the back-bend roller. It will be used if early development dictates the need to fine-tune the bend by unbending the conductor slightly after primary roll-forming. Roller 5 is intended to be used to unroll-form the conductor (i.e. straighten it) if the conductor must be unwound from the form for any reason. It is shown in the retracted position. Roll-bending is performed by the three center rollers (#1, #2 & #3). Force is applied by roll 3 and reacted by 2 and 1. This is a pinch style roll-former which allows the conductor to enter the forming head straight. Roll 2 surrounds the conductor on three sides to bend the conductor and support the sides to minimize sidewall deformation during bending. This roller is fixed in position and is reacts the most force during bending, and is thus considered to be the primary bending roller. The two rollers on either side of the control roller push the conductor against the central roller. They may be driven separately or in combination to effect the proper bend. The diameter of the rolls where they contact the conductor are all the same to minimize conductor slip and attendant metal fine generation during the forming operation.

The plan view above would tend to indicate that the rolls and their drive mechanisms are located below the conductor. In actuality all the equipment in the forming line is located above the conductor centerline and under-hung from a support structure. This allows the winding form to pass freely beneath the forming equipment to whatever extent is called for.

1.4. Winding Support Table and Drive System

The table and drive system must be capable of adapting to the various coil shapes with a minimum of change-over or modification required. The table and drive system depicted below will facilitate the winding of all PF magnet types as well as the TF magnets by simply changing the winding form and control algorithm. The table consists of a mechanism called a lazy-arm. Three large thrust bearings are eccentrically located above each other so the table can achieve an infinite range of positions within the radius of the fully extended position of the three bearings.

The above sketch is intended to illustrate the workings of the three bearing system. In reality the motion of the two lower bearings is fairly limited so operator access is provided to the exterior of the winding form without requiring the operators to stand on the tables. A control algorithm must be generated for each unique geometry which will govern the rotation of the three drive motors. This design provides the needed flexibility so that the winding form may be positioned below the primary forming head in any needed orientation to allow the conductor to be paid into the form as it is bent. This design provides another advantage; the ability of the system to verify proper dimensions of the winding form after reaction by placing the form on the upper table and executing the control algorithm for a given turn about a fixed point other than the roll-forming head. By rotating the form about another point an inspection gage can be placed at that point which will locate the sides of the form which should pass within restrictive boundaries within the gage thereby indicating any distortion of the form and verifying the form is correctly located on the table.

1.5. Winding Form and Conductor Clamping-

A critical part of proper coil winding is the clamping of the conductor in the desired location. This is done with a series of removable clamps. Clamps are located each 18" around the coil form. This has been shown during development to limit the banana gaps between clamping positions to .010" or less. This will provide the dimensional control to insure the necessary build dimensions are met. The form itself will be made to the coil dimensions before

reaction induced conductor shrinkage so that it will be slightly larger than the final desired coil size. The width and height of the cavity are the same as the desired coil dimensions. The .010" clearance between conductors is provided by making the shim undersize. Current plans call for a .062" nominal insulation space between adjacent conductors and half that on the sides between the conductor the nominal ground wrap wall. We will use a shim with a nominal thickness of .050". The shim is not continuous over the entire coil length. Special spacers are needed at the transitions. The spacers will be short strips placed in by hand, since a small gap between adjacent strips will not translate into a local conductor displacement.

The vertical build is controlled by insertion of pins above each layer as a new layer is added. These pins only provide a restraining force, a hydraulic fixture is attached to the top of each clamping station to force the conductor down so the pin may be inserted.

These pins are also used

later to restrain layers as the conductor is paid out for cleaning and insulation.

A .050 shim is used to provide spacing between layers. This spacer will be laser cut to fit the exact geometry of the coil and will be divided into sections small enough to be easy to handle and fit inside the winding cavity. When all the layers have been wound a top cap is placed on the form to hold the conductor in position during banding for the reaction process.

Most of the winding form can be made from cold rolled steel since it will not be placed in the reaction furnace. This will minimize costs of the forms. The fixture will incorporate clearance to allow banding of the coils for reaction.

1.6. Length and twist measurement

Development and analysis indicate that the most

important variable in the forming process is the length of conductor paid out at any time. It is critical to be sure that the proper amount of conductor has been placed in each turn. The conductor is inelastic so we must place exactly the right amount of conductor in a turn. Failure to do so will insure build dimensions can not be met. Measurement of the conductor fed into the bending head is a simple matter. We will use two rotary encoders and a resolver. The encoders will contact the surface of the conductor with a rubber faced wheel which will in turn rotate the encoder. Rotations will translate to length by counting encoder pulses. Two encoders will be used to provide redundant measurement. The resolver will look at the two encoder readings and ensure they are within a small range of each other. Large discrepancies will indicate damage to one of the encoders or wheel slippage. The conductor must be stopped and the problem resolved. This measurement of length is not sufficient to ensure the turns are properly made. The conductor shrinks

during bending since the neutral axis of bending is not on the centerline of the conductor, thus more of the conductor is placed in compression than tension and thus the conductor appears to shrink. The length of material needed for a given turn is thus longer than mathematical calculation (using the bent centerline) would indicate. This length is referred to as the developed length and can only be determined experimentally. This will be done after the winding machine has been fabricated and tested. The winding machine program will be compensated to adjust for the developed length. The encoders will insure the proper amount of conductor is paid out to form the developed length thereby ensuring the turn is properly formed and can be placed in its proper location within the form.

Twist must also be determined during development. A sample coil consisting of several turns must be made to investigate the conductor tendency to twist. This may be done with currently planned hardware but the conductor used must be representative of the material and process to be used to make the production conductor. Twist compensation will be done before the forming operation so the conductor is twisted entering the forming head. The forming head must therefore twist to align with the conductor exiting the twist head. The conductor will then be formed by the forming rollers and exit them in the proper orientation to the form. Twist is not expected to be excessive so the range for the twist mechanism will be limited.

1.7. Helium Stub Welding

Helium stubs attachment requires cutting into the conductor conduit and welding the stubs to the conduit surface. This operation is performed during the conductor roll-forming process. For that reason their position will be located as part of the control algorithm and the system will be stopped when attachment of the stub is called for. The conductor will be locked into place above the form on posts brought in for that purpose. A drill will be mounted directly to the conductor and supported by a fixture during boring of the helium hole. Welding will be likewise performed in-situ. The stub locations will be between the winding clamping supports and will thus not interfere.

1.8. Transition Bending

Turn-to-turn transitions will be generated by the winding machine as it generates the turns themselves. It has been demonstrated that this can be performed without back-bending the conductor. They will then be clamped as the balance of the turn is clamped with the clamping stations being off-set to compensate for the transition. Spacers will be placed as necessary so the transitions may be clamped securely to the supports. The layer-to-layer transitions will be formed using a hand-held hydraulically assisted forming tool similar to but lighter than that used in the development effort. Access will be provided to the inside and outside of the form in the area of the layer-to-layer transitions so the operator may hand-form them. Spacers will be installed to lock the transitions in place for reaction.

1.9. Control System

The control system will be computer based. It will be basically a CNC machine tool control system with the number of axes and hierarchy of control defined by the plan layout. The system must be able to learn i.e. development data must be fed back into the

control algorithm. The system will need to store information pertaining to the specific coil being wound (i.e. PF7, TF etc.). The machine will be "learn" by an iterative process. Preliminary bending information is generated relating roller position to as-bent radii. This information is entered into the control system. Transitions between the different radii are interpolated. A sample coil turn will be wound and inspected. The input information can then be biased to compensate for the as-bent results. Transition stop and start points can also be modified based on the inspection results. A second turn is then wound and further compensation is applied if necessary. The system must be able to be stopped and started from a remote console to facilitate insertion of the spacers and clamping. It must also be capable of being operated in the "jog" mode for hand insulating and maintenance tasks.

Control hierarchy is fairly simple. The length positioning system is the master. It in turn directs positioning of the forming rollers on the roll-former, the winding table position, twist head orientation, and rate of feed of the tractor system. The payout spool drive system will simply react to the needs of the tractor by providing constant dynamic tension on the conductor. The spool is servo-motor driven with the servo rotating the spool enough to maintain the required tension. Up-down motion of the spool will be controlled by remote photo-sensors which will ascertain if the spool should be raised or lowered to keep the payout flat relative to the centerline of the tractor. The straightening rollers will be locked into position during normal operation in a geometric array determined by experimentation to provide suitable straightness of the different conductor types. The three rolls of the straightening system which are used to re-spool the conductor when the machine is backed-up will be controlled by accessing a maintenance routine within the control system and will be manually controlled.

1.10 Lead Forming

Leads are formed after the coil winding is complete and the coil has been banded for reaction. A manual hydraulic tool is used to form the various bends required to place the splice material in the proper position for reaction. Dimensional control of the various turns of the leads are not critical. The leads must not interfere with other equipment and instrumentation in the chimney and the lead termination must be precisely placed to facilitate making the splice joints. The conductor can be bent to fit at this point. We will use a template showing the exact relationship of the conductor to be used for the splice and the coil. Once the shape of the leads is correct they are secured to the coil to support them during reaction. The conductor sheath will not be removed until after reaction and placement of the coil in the case.

A-2. COIL WINDING EQUIPMENT DRAWINGS

PRELIMINARY

PRELIMINARY

PRELIMINARY

DESPOOLER - SIDE ELEVATION

PRELIMINARY

DESPOOLER - PLAN VIEW

PRELIMINARY

THK SLIDE

BALLSCREW

GEAR REDUCER

ELECTRICAL SERVO

REVERSIBLE
STRAIGHTENER/RE-BENDER
MODULE

PRELIMINARY

ELECTRICAL SERVO
(GEAR DRIVES
NOT SHOWN)

THK SLIDE

AIR CYL

REVERSIBLE
PINCH ROLLER
DRIVE MODULE

PRELIMINARY

DE-TWIST
PINCH ROLLER
MODULE

PRELIMINARY

REVERSIBLE
FORM/RE-STRAIGHTENING
MODULE

PRELIMINARY

TF
COIL

PRELIMINARY

PF-1 COIL
PLAN VIEW

PRELIMINARY

PF-7 COIL
PLAN VIEW

PF-7
COIL

A-3. TF COIL PRELIMINARY BENDING PROCEDURE

SCOPE

This procedure establishes the method for winding Toroidal Field (TF) superconducting magnet coils for the Tokamak Physics Experiment (TPX) for Princeton University.

GENERAL NOTES

1. For information regarding safety and proper use of any applicable chemicals, consult the Material Safety Data Sheet (MSDS). These sheets are available from the foreman.
2. All chemicals, when not in use, are to be stored in an approved storage container.
3. All waste (i.e. rags, chemicals, etc.) are to be disposed of properly, in accordance with company policies.
4. Safety equipment (i.e. gloves, safety glasses, coveralls, etc.) are to be worn when applicable. Machine guards should be in place during winding.
5. Precautions are to be taken to maintain the cleanliness of the environment and individual parts. Coils should be covered during idle periods, welding, and machining. Lint-free gloves should be worn when handling the conductor to avoid leaving fingerprints.
6. If any unusual conditions are observed, immediately contact the supervisor.

PURPOSE

The purpose of this procedure is to establish a means to convert spooled TF conductor into a TF coil which subsequently will be reacted in a furnace.

SUPPORTING DOCUMENTS

The following documents form an integral part of the TF Coil Winding Procedure:

Document Name	Document Number
TF Welding Procedure (Nozzle Welding Addendum)	(TBD)
TF Coil Winding Design Drawing	(TBD)
Cleaning Procedure	(TBD)
Material Handling Procedure	(TBD)
MITAP	(TBD)
General QC Procedure	(TBD)
Reaction Nozzle Installation Procedure	(TBD)

ORIGINATOR:

Henry M. Bell

DATE: 6/23/95

OPERATING PROCEDURE

1. Issue conductor and spacer materials for TF coil winding operation. (Reference Bill of Material.)
2. Install the spool of conductor on the de-spooler using a crane and the appropriate lifting fixture (Tool Number TBD).
3. Solvent wipe the winding bobbin and rolls on the roll bender and straightener to assure all surfaces are clean. (Reference Cleaning Procedure TBD).
4. Straighten sufficient conductor to thread the straightener station using the manually operated hydraulically powered straightening/forming tool (Tool Number TBD).
5. Jog the straightener station sufficiently to thread the roll former. Reset the conductor length readout on the roll former controller to zero. Place a reference mark on the conductor to indicate the end of the coil lead. Jog the conductor feed again to provide the adequate conductor for the power lead for the coil (TBD inches) referencing the length readout on the roll former controller. Place a reference mark on the conductor to indicate the start of the lead bend.
6. Finish forming the first radius for the outer turn of the first coil pancake. This pancake is formed from the outer perimeter of the coil inward to the inside of the coil. When there is sufficient conductor (length readout of TBD inches) capture the conduit to the winding bobbin using the appropriate clamp.
7. After initiation of the forming of the first turn (but prior to the seating of the second turn of the coil), install the turn to turn boron nitride coated spacer strip (part number TBD). This spacer strip feeds off a roll which travels with the forming head. It is continuous from initiation at the start of the first layer to the completion of the second to last turn of the second layer of the pancake. During the forming operations secure the spacer strip to the conduit using the conduit clamping stations (see Figure 3). Figure 1 shows the initiation of the spacer strip. The spacer also provides a clamping surface to force the conductor against the winding bobbins coil perimeter supports. The second turn is nested against the first turn (reference Figure 2). As each subsequent turn is added the clamp holding the prior turn is loosened and the conductor turn being laid is laid against the spacer. The clamp is then tightened again (see Figure 3). The roll former will calculate and perform all bending within a coil pancake.

8. When the roll former completes the last turn of the first pancake, it will form the pancake to pancake X-Y plane bend and begin forming the second pancake on top of the first. Just prior to initiating this transition, the controller will halt the roll forming machine. Mark the conductor at the point indicated by the roll former for the manual transition bend. Re-start the roll bender to allow adequate clearance to perform the bend. Since the roll former only performs bends in the X-Y plane, the Z plane bend required to transition from one pancake to another is performed with a manual bender (Tool Number TBD). The roll bender will halt again to allow the operator to perform the transition bend.
9. Attach the bender to the conduit using the transition reference mark. Make the manual bend.

(This bend is in the Z direction.) The co-wound spacer strip is bent simultaneously with the conductor. The manual bending fixture will control the amount of overbend applied to the conductor in forming the Z-axis bend.

10. Figure 4 illustrates this bend. Have an inspector verify the bend geometry and visually inspect the coil pancake for cleanliness and turn to turn spacer placement.

11. Clean, visually inspect, and fit spacers plates (Tool Number TBD) at this time on top of the first pancake to separate the surface of the first and second pancakes. (These are re-usable segmented spacers 0.072" thick shaped to fit the planar contour of the coil).
12. Figure 5 shows, in cross section, the relationship of the spacer plate and the spacer strip. Have an inspector verify the spacer plate is properly placed and seated.

13. The turns of the second pancake are now formed from the inside out with an outward turn to turn transition between each turn. The roll former will perform these bends. As the conduit passes each clamp, the hold down rods are extended to cover the newly laid conduit (see Figure 6). These hold downs are used continuously during winding to restrain the coil and to hold the spacer strip in place.

14. After forming the outward transition for the outermost turn of the second pancake, the controller will stop the roll former and the spacer strip feed. Cut the spacer strip. The spacer strip will be reattached at the appropriate position on the next pancake. Re-start the roll former.
15. Run the roll former until the outermost turn of this second pancake is formed to a point approximately 30° before the power lead bend. The controller will stop the roll former at this point. Mark and have an inspector verify the line indicating the start of the pancake to pancake transition. Restart the roll former to pay out sufficient conduit for the manual bend to be performed and stop the machine. Attach the manual bending machine (Tool Number TBD) and perform the outer transition bend. (This bend is in the Z direction.). Have an inspector verify the geometry of the bend.
16. Install the coolant flow connector (He nozzles) at this time on the outer side of the conduit.. (Reference He Nozzle Installation Procedure, TBD).

17. Figure 7 shows the outer transition bend extending beyond the surface of the coil in position for the nozzle installation. Have an inspector inspect the nozzle weld per the TPX QC plan and visually inspect the surface of the second pancake.
18. Fit spacer plates (Tool Number TBD) at this time on top of the second pancake to separate the surface of the second and third pancakes.

19. Reattach the turn to turn spacer to the conduit using the conduit clamping stations (see Figure 3). Restart the roll former to form the third pancake. Repeat steps 8-20 for pancakes three through eleven. Helium nozzles are installed at the end of pancakes 2, 4, 6, 8, and 10. On the twelfth pancake the process changes slightly. This pancake is an inside diameter to outside diameter winding with the outside turn terminating in the coil lead bend. The process is the same until the last turn.
20. The controller will halt the roll former at the proper point on the last turn to start the lead bend. Mark the indicated bend centerline location for the manual bending operation. Have an inspector verify the location of the mark. Restart the roll bender to pay off adequate conduit to form the coil lead and splice length. Mark the conduit for cut-off. Have inspector verify the position of the cut-off line.
21. Place the spacer plates on top of the twelfth pancake. Attach the hold down plates at each of the clamping stations. (see Figure 8). Cut off extra conduit length, prepare conductor ends

for splicing, and attach helium nozzle for reaction process purging. (Reference Reaction Nozzle Installation Procedure for details.)

22. Attach the manual straightening/bending machine to the the inlet lead of the conduit using the lead bending mark placed on the conduit. Activate the manual lead bender to perform the bend (This is in the X-Y plane). The bend is illustrated in Figure 9. Have an inspector check the lead bend.
23. Install the manually-operated straightening/bending machine (Tool Number TBD) on the outlet coil lead using the reference mark. Have Quality Control verify the placement of the mark. Bend the lead to a radius of TBD inches. (NOTE: This dimension is controlled by the bender tooling, i.e. no operator intervention is required.) This bend is in the X-Y plane.
24. Secure coil leads to the winding bobbin. Visually inspect the coil for cleanliness. Cover the coil with green polyethylene plastic to minimize contamination. The coil is ready for reaction process preparation now.

Figure 9. Showing formation of final lead bend

A-4. TF COIL WINDING MOVEMENT ANALYSIS

A-4. TF Coil Winding Table Movement Analysis

Key issues are the winding table movements, and the number of degrees of freedom required to maintain tangency of the coil with outlet of the bender.

Winding Movements - Supporting Analysis

The "D" shaped TF coil geometry is shown in Figure 1. The arc centers were calculated from the various coil radii and the included angle for each arc. The "x,y" coordinate system and magnet center are also shown in Figure 1.

The path of the coil center to maintain tangency with the bender outlet was calculated. The conductor center is at the intersection of the x axis with the line through the arc centers for the corner radii. The path of the coil center is plotted in Figure 2. The variation of the conductor angular rotation with the center position on the y axis is plotted in Figure 3.

With the bender outlet fixed, it is clear that the conductor coil table must move in three dimensions, x, y and angle of rotation, relative to the bend head. No matter what the configuration of the bender and/or the coil table, three degrees of freedom are required.

It is not obvious from the proposal concept sketches that all of the proposed winding concepts meet this requirement. The station referred to as "Coil Concept A" is shown in Figure 4. In the sketch the table is shown to rotate, and the bender is shown to move radially in and out. No side-to-side motion of the table or the bender is indicated. For the position shown, if the table rotates either the bender will no longer be tangent to the coil, or the bender must rotate and kink the straight ahead of the bender. Side-to-side motion of either the table or the bender is necessary.

Concept B shown in Figure 5 rotates the conductor coil table and moves the conductor spool from side-to-side. The "tangent correction" feature allowing the bender to rotate about the spool axis provides a limited range of top to bottom motion depending on the spool diameter and the range of angular motion. However, the "tangent Correction" shown in the right hand figure appears to be on the wrong side of the horizontal centerline if the conductor is to be delivered tangent to the coil. Other difficulties with this design are the vertical stack-up, and operating clearances among the components over and under the bender. The conductor spool cannot move vertically downward because it would interfere with the winding table. Consequently, the conductor must wind off the spool from a variable distance above the winding table, increasing the helix angle of the conductor entering the bender.

We believe the conductor spool axis, the straightener centerline, and the bender centerline should be fixed relative to one another, and that the conductor table should be moved relative to the bending rolls for winding the conductor.

Figure 1 Plot of TF Magnet Coil Inner Contour and Center Point

Figure 2 Winding Path of TF Magnet Coil Center
(Coil Tangent to Bender Outlet)

Figure 3 Plot of Magnet Angle of Rotation (angd1) versus y Axis Coordinate of Coil Center

A-5. COIL BENDING ACCURACY ANALYSIS

Bending/Winding Accuracy

The two key factors controlling the accuracy of the coil winding operation are:

Bend Radius, and
Arc Length.

In fitting the coil up to the form, it may be possible to adjust the bend radius. The length cannot be adjusted!

Bend Radius

For the relatively large coil bend radii, the bend radius can be adjusted slightly by springing the bend to either open or close the bend. Thus, some deviation from the nominal bend radius is tolerable, as long as the bend radius is **uniform**. While a non-uniform bend radius can be sprung, the non-uniformity will remain, and the non-uniform section will not fit-up with adjacent turns.

When coiling **inside to outside**, a slight overbend is preferred. A low tension level on the winder will spring the bend open to fit around the previous turn. Elastic springback will hold the conductor tightly to the previous inner turn. An under bend would require tension winding to hold the conductor against the preceding turn.

When coiling **outside to inside**, a slight underbend is preferred. The bend is sprung elastically to fit inside the previous turn. The bend then springs out and is constrained by the previous outer turn. An overbend would have to be sprung open and held in place. Elastic springback would cause the conductor to pull away from the previous outer coil leaving a gap.

In summary:

1. Bend uniformity is required.
2. Coiling inside to outside, the bend radius tolerance should be to the minus side.
3. Coiling outside to inside, the bend radius tolerance should be on the plus side.

Arc Length

The length of the conductor may change slightly during bending depending on the location of the neutral axis relative to the centerline of the conductor. The conductor will stretch if the neutral axis lies inside of the bend centerline, and shrink if the neutral axis is outside of the conductor centerline. This effect must be allowed for in the control of the winding machine. The length of the conductor cannot be changed to fit the contour form. Consequently, the length of each arc segment must be tightly controlled.

Accurate measurement of the conductor length on the outside of the bend, inside of the bend, and the conductor height can be used to estimate the bend radius and the neutral radius. The average outlet feed relative to the inlet feed determines the bend stretch or shrinkage.

To estimate the required length accuracy, an analysis was made for the 3 TF magnet bend radii. For the full arc, and for an 18" chord length, the arc to produce a specified radial gap was calculated. The construction is shown graphically in Figure 1 for a much larger radial gap.

The variation of the differences in bend radius and arc length with gap for the 41.4" bend radius 90 degree bend are shown in Figure 2. The variations are linear for a gap range from 0 to 0.020". For a 0.010" gap, the bend radius is 0.0242" oversize, and the arc length is 0.0104" short.

The results for the three conductor bend radii with a 0.010" gap are listed in Table 1 for the full bend arc and for an 18" chord length. The key items are the differences in the bend radii and the arc length between the nominal values and the values calculated for a 0.010" radial gap.

For the 41.4" radius, the full arc length must be accurate to within 0.0242" to hold the gap under 0.010". For the 18" chord length the required accuracy is 0.0029". Dividing the arc length difference by the arc length gives a required accuracy of 0.00016 in./in. for the 41.4" radius.

For the 60.7" radius the accuracy requirement is 0.00011 in./in., and for the 228.7" radius 0.000028 in./in. The largest bend radius requires the highest accuracy.

The winding machine gauging will measure to 0.0001", which is sufficient for the tighter bend radii. The larger 228.7" bend radius may have to be fitted and held in position.

Gap set large to show procedure. $g = 5$

Figure 1 Gap between Arcs with Common Chord Length

Bend Radius: $R1 = 41.4$
 Bend Angle: $2 \cdot Ang1d = 90$

Figure 2 Difference in Bend Radius and Arc Length versus Gap

Table 1 TF Coil Arc Length and Bend Radius Variation for a 10 mil Gap
(for the Full Arc and for an 18" Chord)

<u>Bend</u>	<u>Chord Length</u> inches	<u>Aim:</u>		<u>Calculated for 10mil Gap</u>		<u>Difference</u>		<u>Arc Length Accuracy</u> for 10mil Gap
		<u>Bend Radius</u> inches	<u>Arc Length</u> inches	<u>Bend Radius</u> inches	<u>Arc Length</u> inches	<u>Bend Radius</u> inches	<u>Arc Length</u> inches	in/in
Full Arc	58.5484	41.4	65.031	41.4242	65.0206	.0242	.0104	.00016
18" Chord	18		18.1449	41.8124	18.1420	.4124	.0029	.00016
Full Arc	78.7528	60.7	85.6941	60.7319	85.6847	.0319	.0093	.00011
18" Chord	18		18.0666	61.6083	18.0646	.9083	.0020	.00011
Full Arc	72.4353	228.7	72.7415	229.4852	72.7394	.7852	.0012	.0000290
18" Chord	18		18.0046	242.3715	18.0041	13.6715	.00051	.0000283

Section B. COIL REACTION FURNACE

- B-1. Process Description
- B-2. Equipment Drawings
- B-3. Preliminary Procedures
- B-4. Reaction Temperature Uniformity Analysis

B. Coil Reaction

B-1. Process Description:

The Niobium-Tin reaction process diffuses the Sn into the Nb to form the intermetallic Nb_3Sn . This process must be carefully controlled and monitored to prevent damage to the expensive superconductor. The atmosphere must not contain more than 0.1 PPM of oxygen to prevent stress induced cracking (SAGBO) of the Incoloy sheath at the high curing temperature. This will be ensured by performing the high temperature portion of the reaction cycle under a fairly high vacuum ($<1 \times 10^{-4}$ Torr). Atmospheric integrity will be assured by sampling the pump-out gas with an on-line gas analyzer.

After prevention of SAGBO, the next most important factor in proper heat treatment of the conductor is uniform temperature during reaction. Several factors interact here to facilitate uniform heating; proper zoning and location of heaters, thermal conductivity properties of spacer material and atmosphere. Radiation heat transfer at low temperatures is very inefficient. This was predicted by thermal modeling and confirmed by heat transfer matrix testing in B&W's anneal retort in which a model of the TF geometry was heated to the proposed reaction temperatures and results monitored. Heat transfer can be greatly enhanced at low temperatures by using an inert gas at a low partial pressure. Test results indicate argon works well in this application. Helium and argon systems will have active gas cleaning systems. Argon is used so a leak can be distinguished from a helium leak in the purge system and due to the precedent established on US-DPC. The argon is introduced after the reaction chamber has been evacuated. Test results indicate a pressure of 1 Torr is adequate to provide significantly improved heat transfer below 340°C. The argon is pumped out to effect a hard vacuum before heating the conductor up to the final reaction temperature of 650°C.

Development results also indicate some sintering may be experienced between the conduit surface and the spacer material placed in the winding form to space the individual conductor turns. Testing indicates that this sintering can be basically eliminated through the application of a boron-nitride coating to the surfaces of the spacer material before use. Plans call for the application of the coating using flame spraying in production rather than aerosol spraying as was done in testing. The aerosol coating is too fragile. Testing of stainless steel and copper spacers is being performed in the reaction development program. Results are not yet available for comparison purposes. Thermal modeling, though, predicts significantly better heat transfer and thus more uniform heating with the copper spacers. Pending confirmation of this preliminary indication, copper spacers will be recommended providing the potential for oxygen liberation from a copper oxide coating on the copper can be eliminated as a concern.

Heater placement and zoning are critical to proper and uniform radiation heating. Since the heat treatment is a relatively low temperature thermal cycle exotic heat element materials such as Molybdenum and Tungsten are not called for. Geometry and zoning will need to be flexible to some extent. Zoning flexibility can be accomplished by cutting off unneeded zones when heating the smaller PF coils. This will require the use of a large

number of zones which will translate into an extensive zone control system. This impact can be minimized by setting up the zones up so that some portion of the elements can be disconnected for heat treating PF coils providing the control system moderates the zone power to account for the decrease in heating elements. Radiation heating is by line-of-sight which means it is increasingly inefficient when heat is supplied at some angle other than perpendicular to the part. For this reason, provision has been made for removable zones to be added to the reaction form prior to placing the form in the furnace if required. They are then plugged into the furnace after it is loaded. These zones will be inside the coil form and will face the inner walls of the PF and TF coils. The geometry of the removable zones will thus depend on the coil type being reacted. Otherwise the inside can only be heated from the furnace roof and to a lesser extent the bottom and sides. This is not efficient and preliminary thermal modeling indicates a non-uniform heat distribution during heat-up.

Thermal modeling has further indicated the need for active wall cooling during the cool down cycle. After the coils have cooled to 350°C, argon is introduced to the furnace to enhance heat transfer during the cool down period. In order to draw the heat out of the argon active wall cooling is used. This is strictly a through-put issue. Capital cost is traded off against reaction cycle time. The coil can be completely cooled through the walls to the room, this will add days to the thermal cycle.

There are other less critical issues relating to the reaction furnace and process. The leads must be supported throughout the process and allowed to expand as they are heated but not distort due to stress relaxation. They must be protected as well when unloading the furnace since they will be brittle after the reaction cycle. FMECA has identified this as a high risk item. These features will be added to the reaction fixture in Phase II of the contract, and qualified in heat treating the dummy coils late in Phase II. Adjustments called for as a result of prototype testing can then be added.

As mentioned above, stress induced cracking of the Incoloy conduit must be prevented. A hard vacuum in the reaction chamber will protect the external surface of the conduit but the inside must be protected as well. Impurities are introduced to the conductor during the wire fabrication and cabling process, as well as during the process of encapsulating the cable in the Incoloy sheath. The conduit must be protected from oxygen given off during vaporization of any of these impurities during the reaction cycle. This is facilitated by flowing helium through the conductor during the reaction process. The helium will contain roughly 2% of hydrogen, which is added to the helium by the supplier. The hydrogen will combine with the liberated oxygen to prevent it from doing damage to the inner walls of the conduit. The impurities are then swept away by the helium stream before they are allowed to concentrate.

The three sketches in section B-2 show the reaction furnace layout.

The furnace chamber depicted has the ability to heat treat two TF coils in one furnace load. This capability was built into the equipment to mitigate schedule risk. The reaction cycle takes approximately 22 days and is thus the program schedule limiter. We would not plan to heat treat two coils due to the cost risk of losing two at once should we encounter system difficulties requiring us to abort the reaction cycle. This capability is built into the design strictly as a contingency useful in schedule recovery. The two coil concept does highlight the need for removable heat zones to be placed within the coil during reaction. It would be virtually impossible to adequately heat the inside of the coils given the shielding provided by the adjacent coil and the structure of the coil winding support for each coil without internal zones.

COIL LAYOUT IN REACTION FURNACE

The concept drawings show insertion of two TF coils. The furnace has been sized to accommodate coils PF 1-5 as well. Support tooling for the specific designs will be required but this is minor. Heat zones will need to be arranged as noted above but this is simply a matter of physically or electronically reconfiguring the zones for the coil to be reacted. All

the coils will be reacted with the primary surfaces parallel to the floor as illustrated with the TF coils in the top view above, with the exception of PF1-4 uppers which have long leads. Those coils will be turned on their side so the lead length can be accommodated. Special fixturing will be required to support them in this orientation but will be simpler, less expensive and far less risky than providing a special top heat zone to react the long leads extending above the top of the main chamber. The furnace will then have four primary zone configurations: TF magnets, PF5 magnets, PF1-4 lower and PF1-4 upper. Inclusion of PF magnets in this furnace design is thus a simple task and can be accommodated in the basic design.

The process flow diagram below provides a simplified process sequence which includes the introduction of low pressure argon to enhance heat transfer both during heat-up and cool-down. The cycle also includes active cooling during the final cool-down portion of the cycle. This cycle is basically one of the cycles being used by potential superconducting strand vendors competing for the strand award for the TF and PF magnets. The reaction system will not be hard wired with this sequence, all the process parameters such as hold times and temperatures are program adjustable so the system can be altered to provide the selected strand heat treat cycle. Different cycles can be run for the different coil types as

Coil Reaction

well should the University award the strand supply contracts to vendors having different heat treatment cycles. Further details can be found in the draft reaction procedure, section B-2. The reaction furnace specification is provided in SDRL 20.

B-2 COIL REACTION EQUIPMENT DRAWINGS

FRONTAL VIEW

8/1/95

Babcock & Wilcox
TF Magnet Preliminary Design

SDRL 22 Mfg Equipment Drawings,
Specifications, and Procurement Plans

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A2/a (Cont) Subsystem Name: Cable (CICC) Component Name: Conduit		Function: Incoloy 908 structure which provides a sealed conduit for He coolant flow and structural support of the superconducting cable.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: He leak)	<p>ii) "SAGBO" of Incoloy 908, due to oxygen or water present during the Nb₃Sn reaction process:</p> <p>a) internal to the conductor; outgassing of conductor materials, from contaminants introduced in the CICC during processing, from He supply.</p> <p>b) external to the CICC; from tooling, from the furnace, from the Argon supply, due to vacuum fault, non-uniform pressure distribution in chamber.</p>							<p>Reaction Equipment Specification", TPX-SPEC-133-0003</p> <p>4) Coil reaction: The atmosphere inside the furnace will not contain more than 0.1 PPM of oxygen. The reaction cycle will be performed under a vacuum ($<1 \times 10^{-4}$ Torr). The pump out gas will be sampled with an on line gas analyzer. To aid heat transfer, Argon is introduced after the reaction chamber has been evacuated to a 1 Torr vacuum and the coil is heated up to 340°C. The argon is then pumped out to effect a hard vacuum before heating the conductor up to the final reaction temperature of 650°C.</p>
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A2\la (Cont) Subsystem Name: Cable (CICC) Component Name: Conduit		Function: Incoloy 908 structure which provides a sealed conduit for He coolant flow and structural support of the superconducting cable.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: He leak)	iii) Crack initiation and growth in the leads, particularly the module to bus leads which may experience significant handling, transportation, and operational stresses (thermal and magnetic cycling [PF pulsing, and TF cycling], as well as plasma disruption).							Helium (with 2% of hydrogen, intended to combine with any liberated oxygen) will be flowed in through the conductor during the reaction process to sweep away any impurities. See "TF Coil Reaction Procedure", OP TPX-00002, and "TPX Coil Reaction Equipment Specification", TPX-SPEC-133-0003 for further details. 5) Leak test, NDT - weld inspection, and crack detection after the reaction procedure will be performed per the "Material & Component Test Plan", TPX-PLAN-MCTP, and "Coil Verification Test Plan", TPX-PLAN-VTP.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A2\ b Subsystem Name: Cable (CICC) Component Name: Conduit		Function: Incoloy 908 structure which provides a sealed conduit for He coolant flow and structural support of the superconducting cable.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	1) Base material weakness. 2) Twist in conduit produced at the spooling or coil forming operation. 3) Local kink/buckle produced during the spooling or coil forming operation. 4) "SAGBO". See prior sheet, TFQD22A2\ a for causes and mechanisms of this phenomena. 5) Overstrain/low cycle fatigue due to spooling and coil forming operations. 6) Mechanical damage; drawing, compression. 7) Excessive residual strain.	1) Nonconforming coil can lead to ramp rate limitations or quench prior to operating current. 2) Nonconforming coil can lead to plasma containment field error.	1) Assembly: Visual inspection, NDT. 2) Operation: Limitation in coil's performance.	None		D	II	1) LLNL will perform multiple inspection operations of the CICC prior to delivery to B&W. 2) B&W will perform multiple inspection operations of the CICC throughout the assembly process (per the manufacturing Operating Procedures) to detect, and if possible correct, any nonconformance. 3) See prior failure mode, TFQD22A2\ a for prevention efforts against the "SAGBO" phenomena.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A2\c Subsystem Name: Cable (CICC) Component Name: Conduit		Function: Incoloy 908 structure which provides a sealed conduit for He coolant flow and structural support of the superconducting cable.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Inadequate He flow	1) Localized material buildup of particulate such as: weld slag, grinding dust, corrosion, solder particulate, Cr flakes. 2) Frozen He contaminants. 3) High heat load causing vapor lock. 4) He in different flow regime than expected.	Inadequate cooling of the coil can result in possible quench.	1) Quench monitoring. 2) Coolant flowmeter or pressure sensor may detect condition.	None		C	III	1) PPPL Refrigeration System to provide high purity He. 2) Weld qualification and welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. 3) TPX project to monitor instrumentation data.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A3a Subsystem Name: Cable (CICC) Component Name: Non-Inductive Voltage Tap		Function: Detect quench, using a "balanced bridge" algorithm on adjacent double pancakes, as it begins to occur to prevent catastrophic damage to the magnet.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Wire shorted to superconducting cable or conduit.	1) Insulation defect; voids, pinholes. 2) Insulation cut by the 304SS tape during cabling operations. 3) Damaged during assembly; damage or degradation by Nb ₃ Sn reaction temperatures, or Helium stub boring and weld, stretched/crushed during coil winding, lead termination-splice joint welding process, cut/stretched/ kink induced at splice joint termination. 4) Damaged during operation; radiation/ cryogenic degradation, thermal cycling induces localized strain.	Loss of this quench detection circuit; if normal zone undetected by other techniques, resultant damage to magnet.	1) During assembly, test after conduit weld and at TF installation (looking for an expected resistance value based on cable length). 2) Operation, detection through permanent resistance misreading due to incorrect cancellation of inductances between double pancake measurements.	None		C	III	1) LLNL to ensure integrity of the voltage taps. 2) LLNL to qualify cable for TPX life cycle environments. 3) He stub boring and weld process will be qualified by WEC. 4) Splice joint forming procedures will be developed in Phase II. 5) Voltage tap testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A3/a (Cont) Subsystem Name: Cable (CICC) Component Name: Non-Inductive Voltage Tap		Function: Detect quench, using a "balanced bridge" algorithm on adjacent double pancakes, as it begins to occur to prevent catastrophic damage to the magnet.				
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO SC
(continued: Wire shorted to superconducting cable or conduit)						6) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A3\6 Subsystem Name: Cable (CICC) Component Name: Non-Inductive Voltage Tap		Function: Detect quench, using a "balanced bridge" algorithm on adjacent double pancakes, as it begins to occur to prevent catastrophic damage to the magnet.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Open	1) Damaged during assembly; by conduit welding process, Nb ₃ Sn reaction temperatures, or Helium stub boring and weld, during coil winding, during splice formation, cut induced at termination. 2) Wire weld joint fractures and opens. 3) Damaged during operation; thermal cycling or Lorentz forces acting on cable, causes open. 4) Operation; latent defect of the wire.	Loss of this quench detection circuit; if normal zone undetected by other techniques, resultant damage to magnet.	1) During assembly, test after conduit weld/coil winding/ and at TF Magnet assembly. 2) Operation, detection through persistent misreading.	None		C	III	1) LLNL to ensure good QA of voltage taps. 2) LLNL to qualify cable for radiation/ temperature (weld induced temps and cryogenic). 3) Voltage tap testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A4\la Subsystem Name: Cable (CICC) Component Name: Fiber Optic Quench Sensor		Function: Detect quench, through continuous interferometric measures or reflectometry, as it begins to occur to prevent catastrophic damage to the magnet.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Disconnected or open	<p>1) Damaged during assembly; during cabling, by conduit welding process, Nb₃Sn reaction temperatures, or Helium stub boring and weld, during coil winding, during splice formation, cut induced at termination.</p> <p>2) Damaged during operation; thermal cycling or Lorentz forces acting on cable, causes open.</p> <p>3) Operation; latent defect of the fiber.</p>	Loss of this quench detection circuit; if normal zone undetected by other techniques, resultant damage to magnet.	<p>1) During assembly, test after conduit weld/coil winding/ and at TF Magnet assembly.</p> <p>2) Operation, detection through persistent misreading.</p>	None		C	III	<p>1) LLNL to ensure good QA of fibers.</p> <p>2) LLNL to qualify fiber for radiation/ temperature (weld induced temps and cryogenic).</p> <p>3) Fiber optics testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22B/a Subsystem Name: Winding Pack Component Name: He stub		Function: Provides for the transfer of He between the conduit and the He supply/return lines, necessary to keep the superconductor at the required cryogenic temperatures.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He Leak.	1) Incorrect weld design. 2) Incorrect welding methodology for Incoloy 908. 3) Improper weld or fatigue due to thermal, quenching, magnetic, vibration, or seismic cycles. 4) Overpressure, from quench. 5) Defect in base material.	1) If a weld failure where the cooling lines "Tee" into the conductor, at the pancake to pancake crossovers, He may accumulate and generate helium pressure (near the Paschen curve minimum) within the confines of the potted coil, a coil short will occur, given a simultaneous insulation breakdown. 2) Degrade/destroy cryostat vacuum which results in increased refrigeration load, eventual TPX downtime.	1) Coil shorted. 2) Vacuum pressure gauge.	None.		C	II	1) WEC to develop and qualify He Stub design and installation process. 2) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b. 3) Leak test and NDT -weld inspection will be performed per the "Material & Component Test Plan", TPX-PLAN-MCTP, and "Coil Verification Test Plan", TPX-PLAN-VTP. 4) TPX project to monitor instrumentation data.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22B\A (Cont) Subsystem Name: Winding Pack Component Name: He stub		Function: Provides for the transfer of He between the conduit and the He supply/return lines, necessary to keep the superconductor at the required cryogenic temperatures.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: He Leak)								5) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22B1b Subsystem Name: Winding Pack Component Name: He stub		Function: Provides for the transfer of He between the conduit and the He supply/return lines, necessary to keep the superconductor at the required cryogenic temperatures.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Inadequate He flow.	<p>Restricted He flow in the CICC/He stub due to:</p> <p>1) Damage to the conductor and improper removal of 304SS wrap during helium stub installation.</p> <p>2) Foreign particle introduction (i.e., metallic particles from the boring and welding process).</p>	Inadequate cooling of the coil can result in possible quench.	<p>1) Quench monitoring.</p> <p>2) Coolant flowmeter or pressure sensor may detect condition.</p>	None.		C	III	<p>1) WEC to develop and qualify He Stub design and installation process.</p> <p>2) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET

Item No. TFQD24\ Subsystem Name: Winding Pack Component Name: Insulation		Function: Electrically insulate conduit between turns, layers, and to ground plane. The epoxy fills voids inside the winding pack and serves as a structural bonding agent that bonds the coil turns into an integral structure. Glass cloth serves as a structural reinforcement to the epoxy and provides for an improved matching of CTE between the insulation system and the conduit.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrical short.	1) Kapton wrap nonconformance due to: a) Material defect; holes, thickness, puncture. b) Improper overwrap. 2) S glass wrap nonconformance due to: a) Material defect ; de-size, contamination, dimensional, glass content by axis. b) Overlap. c) Damage in turn-turn layer. d) Filler misplacement or twist. 3) Foreign object (e.g., chips).	1) Loss of coil or loss of coil capacity: a) Shorts in coil. b) Voltage breakdown. 2) Increased quenching.	1) Coil short. 2) Premature quench. 3) Change in coil resistance (at room temperature).	N/A		C	II	1) Insulation system to be qualified by WEC. 2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c. 3) Manufacturing will ensure proper storage of insulating materials as well as storage requirements for the octant. Details in Phase II. 4) Cracks/voids present during fabrication will be per the "TPX TF Coil Specification", TPX-SPEC-133-00001.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD24a (Cont) Subsystem Name: Winding Pack Component Name: Insulation		Function: Electrically insulate conduit between turns, layers, and to ground plane. The epoxy fills voids inside the winding pack and serves as a structural bonding agent that bonds the coil turns into an integral structure. Glass cloth serves as a structural reinforcement to the epoxy and provides for an improved matching of CTE between the insulation system and the conduit.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Electrical short.)	<p>4) Joggle spacers shaped wrong, leading to; resin rich areas, cracks, improper stress distribution, gaps, cut insulation.</p> <p>5) Damage of coil pack insulation during handling and installation in VPI form.</p> <p>6) Improper VPI process:</p> <p>a) Contaminated epoxy; dirty, wrong mix, shelf life.</p> <p>b) Glass contamination preventing wetting. Sizing removal or compatibility.</p> <p>c) Wrong amount of catalyst.</p>							<p>5) Manufacturing will ensure cleanliness per Operating Procedure, OP-TPX-0003.</p> <p>6) Manufacturing will develop handling procedures, attention to protecting winding pack integrity.</p> <p>7) Welding process development at Westinghouse to qualify He Stub weld, prevent He leakage.</p>
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD24a (Cont) Subsystem Name: Winding Pack Component Name: Insulation		Function: Electrically insulate conduit between turns, layers, and to ground plane. The epoxy fills voids inside the winding pack and serves as a structural bonding agent that bonds the coil turns into an integral structure. Glass cloth serves as a structural reinforcement to the epoxy and provides for an improved matching of CTE between the insulation system and the conduit.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Electrical short.)	<p>d) Voids in coil pack epoxy/glass impregnation due to inadequate outgassing.</p> <p>e) Won't properly cure, resulting in inadequate strength.</p> <p>f) Incorrect cure cycle; leak into vacuum, abnormal pressure event, temperature error.</p> <p>7) Damage to insulation during winding pack installation into coil case and during the performance of closure welds.</p> <p>8) Differences in CTE causing shear and tensile stress in insulation.</p>							<p>8) B&W to qualify coil case closure welding per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Manufacturing mockups will be used to verify that no damage to the winding pack occurs during this welding operation.</p> <p>9) Insulation testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD24/a Subsystem Name: Winding Pack Component Name: Insulation		Function: Electrically insulate conduit between turns, layers, and to ground plane. The epoxy fills voids inside the winding pack and serves as a structural bonding agent that bonds the coil turns into an integral structure. Glass cloth serves as a structural reinforcement to the epoxy and provides for an improved matching of CTE between the insulation system and the conduit.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Electrical short.)	9) Electrical overstress during quench or electrical testing. 10) Fatigue failure from cooldown or energization cycles. 11) Stresses due to PF fields (especially in center post). 12) Presence of He gas resulting from conduit leak, conduit seam/butt weld or He stub leaks. 13) Corona failure at voids or fissures. 14) Cracks in insulation present in fabrication, or appearing thereafter. 15) Excessive shear in the insulation due to "Hot spot" during quench.							

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31\la Subsystem Name: Lead Box Internal Assy Component Name: Coil to Coil Splice Joint		Function: Provide for the electrical interface between the two superconducting coils in an octant.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
High resistance	<p>1) Fracture of Nb₃Sn during solder or splice formation (conduit removal, Cr strip, Cu block/solder operations, coil leads alignment, bolting) - post reaction strain limitation exceeded.</p> <p>2) Solder reflow during seal welding.</p> <p>3) Cross contamination between welding & solder operation.</p> <p>4) Fatigue due to thermal (CTE differences) or magnetic cycling (including plasma disruptions).</p>	<p>1) Low current through coil cable; degradation of magnetic field. Could lead to termination of TPX experimental run.</p> <p>2) Increased heat generation at the joint, added refrigeration thermal load, quench.</p>	<p>1) Voltage taps to detect the increased resistance during operation.</p> <p>2) Degradation of magnetic field</p>	None		D	II	<p>1) Process development and room ambient test per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>2) Splice joint to be qualified for TPX operation (MIT tests?).</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31\lb Subsystem Name: Lead Box Internal Assy Component Name: Coil to Coil Splice Joint		Function: Provide for the electrical interface between the two superconducting coils in an octant.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Splice block mechanical failure (causing open or high resistance)	<p>1) Bolts not properly tightened at installation or become loose during operation.</p> <p>2) Case unable to properly accommodate cyclic thermal/magnetic environment in the joint (maintain compression).</p>	<p>1) Low current through coil cable; degradation of magnetic field. In the severe case, high resistance of joint, terminate TPX experimental run.</p> <p>2) Damage to Nb₃Sn cable.</p>	<p>1) Change in resistivity via voltage taps.</p> <p>2) Degradation of magnetic field.</p> <p>3) Excessive boil of cryogen, detected by flow meters.</p>	Check bolts torque while performing scheduled or corrective maintenance for other assembly.		D	II	<p>1) Splice joint to be qualified for TPX operation (MIT tests?).</p> <p>2) Use of a locking device or material on bolts (differential fasteners?). Details to be worked out in Phase II.</p> <p>3) Current design incorporates support elements to the splice joint to react cyclic loads.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31\c Subsystem Name: Lead Box Internal Assy Component Name: Coil to Coil Splice Joint		Function: Provide for the electrical interface between the two superconducting coils in an octant.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He leak	1) Failure of a CICC to joint case interconnect. 2) Improper weld. 3) Fatigue due to thermal, quenching, magnetic or seismic cycles. 4) Overpressure, during quench. 5) Failure of the splice joint solder end cap.	1) He leak of this joint will result in a degraded cryostat vacuum, an increased refrigeration load, eventual TPX downtime. 2) Inadequate cooling of the joint can result in increased resistance, possible quench.	1) Voltage taps may detect the increased resistance due to heating. 2) Flow meter may detect.	None		C	III	1) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b. 2) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 3) Splice joint to be qualified for TPX operation (MIT tests?). 4) TPX Project to monitor instrumentation data. 5) TPX project to consider vacuum pressure gauge.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31\d Subsystem Name: Lead Box Internal Assy Component Name: Coil to Coil Splice Joint		Function: Provide for the electrical interface between the two superconducting coils in an octant.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Inadequate He flow.	1) Welding material contaminants, restrict He flow throughout the joint. 2) He impurities. 3) He leak. 4) Flow meter failure.	1) Inadequate cooling of the joint can result in increased resistance, possible quench. 2) Inadequate cooling will result in excessive thermal load in splice.	1) Voltage taps may detect the increased resistance due to heating. 2) Flow meter may detect condition.	None		C	III	1) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b. 2) Monitor of instrumentation data by PPPL. 3) Monitor of He purity by PPPL.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31Aa Subsystem Name: Lead Box Internal Assy Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate splice joints from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrically shorted.	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p> <p>3) Flashover through gaseous He generated during a quench, and the high voltages (up to 15kV).</p> <p>4) Contamination: conductive particles, oils.</p> <p>5) Frost buildup on exterior body of insulator due to TPX Cryostat leak.</p>	A short to the He lines causing major damage to the insulator and surrounding components.	Loss of TF magnet system operation.	None.		C	II	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Isolator safety factor of 10 times required length under normal conditions.</p> <p>4) Isolators will be tested as part of an assembly kit per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>5) TPX project responsible for Cryostat integrity.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31A\b Subsystem Name: Lead Box Internal Assy Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate splice joints from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He Leak	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p> <p>3) Weld failure.</p>	<p>1) Inadequate cooling, can result in excessive heating and increased quench frequency, by decreasing the conductor temperature margin. Inability to remove the operational heating sources.</p> <p>2) Degrade/destroy cryostat vacuum which results in increased refrigeration load, eventual TPX downtime.</p>	<p>1) Increased quenching.</p> <p>2) Flow meter/ pressure gauge may detect.</p> <p>3) Vacuum pressure gauge.</p>	None		C	III	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) Weld qualification and welder certification per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31B\la Subsystem Name: Lead Box Internal Assy Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Incorrect reading	1) Component failure. 2) Instrumentation out of calibration. 3) Pressure oscillations in plumbing. 4) Impurity material buildup in flow sensor leading to incorrect readings. 5) Erosion. Cause 4 & 5 due to particulate such as weld slag, grinding dust, corrosion.	1) Failure to detect quench by this quench detection circuit on splice joint; if normal zone undetected by other techniques, resultant damage to joint/leads. 2) False indication of quench will be ignored by system if other techniques do not sense quenching of the joint.	1) Transient or erratic reading. 2) Persistent incorrect reading. 3) TPX instrumentation software could detect problem by setting upper and lower bounds of correct operation.	1) Calibration. 2) Replace marginal units at earliest convenience.		C	IV	1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits. 2) Cleanliness control during assembly/storage. 3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) TPX project has responsibility for adequate purging of the system. 5) TPX project to monitor He quality from TF refrigeration system.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31B\b Subsystem Name: Lead Box Internal Assy Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Pressure sensing tubing blockage (if sensor of this type)	1) Foreign object (weld slag, grinding dust, corrosion) or He impurity.	Inaccurate or no flow reading. Loss of this quench detection circuit on the splice joint; if normal zone undetected by other techniques, resultant damage to the joint/leads..	Persistent incorrect reading.	None		C	IV	1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits. 2) Cleanliness control during assembly/storage. 3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) TPX project has responsibility for adequate purging of the system. 5) TPX project to monitor He quality from TF refrigeration system.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD31C/a Subsystem Name: Lead Box Internal Assy Component Name: Intermodule Splice		Function: Detect quench, through continuous interferometric measures or reflectometry or using a "balanced bridge" algorithm on adjacent double pancakes, as it begins to occur to prevent catastrophic damage to the joint.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Cable Instrumentation failure	Open/shorted voltage tap/fiber optics due to: 1) Damaged during splice formation, cut induced at termination. 2) Damaged during operation; thermal cycling or Lorentz forces acting on cable, causes open. 3) Operation; latent defect of the wire/fiber.	Loss of this quench detection circuit; if normal zone undetected by other techniques, resultant damage to magnet.	1) During assembly, test after conduit weld/coil winding/ and at TF Magnet assembly. 2) Operation, detection through persistent misreading.	None		D	III	1) LLNL to qualify quench detection sensors for TPX life cycle environments. 2) Splice joint forming procedures will be developed in Phase II. 3) Quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits. 4) Quench detector testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD32A/a Subsystem Name: Lead Box Internal Assy Component Name: He lines		Function: Supply/collect the He necessary to keep the superconductor at the required cryogenic temperatures.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He Leak	1) Assembly error. 2) Improper weld or fatigue due to thermal, quenching, magnetic, vibration, or seismic cycles. 3) Overpressure. 4) Defect in base material.	1) Inadequate cooling, can result in excessive heating and increased quench frequency, by decreasing the conductor temperature margin. Inability to remove the operational heating sources. 2) Degrade/destroy cryostat vacuum which results in increased refrigeration load, eventual TPX downtime. 3) He may accumulate within the confines of the TF lead box, arcing may occur (Paschen curve minimum), given a simultaneous insulation breakdown.	1) Increased quenching. 2) Flow meter/ pressure gauge may detect. 3) Arcing. 4) Vacuum pressure gauge.	None		C	II	1) Weld qualification and welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. 3) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) Insulation testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. 5) TPX project to monitor instrumentation data.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD32C/a Subsystem Name: Lead Box Internal Assy Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate coils from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrically shorted.	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p> <p>3) Flashover through gaseous He generated during a quench, and the high voltages (up to 15kV).</p> <p>4) Contamination: conductive particles, oils.</p> <p>5) Frost buildup on exterior body of insulator due to TPX Cryostat leak.</p>	A short to the He lines causing major damage to the insulator and surrounding components.	Loss of TF magnet system operation.	None.		C	II	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Isolator safety factor of 10 times required length under normal conditions.</p> <p>4) Isolators will be tested as part of an assembly kit per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>5) TPX project responsible for Cryostat integrity.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD32C\b Subsystem Name: Lead Box Internal Assy Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate coils from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He Leak	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p>	<p>1) Inadequate cooling, can result in excessive heating and increased quench frequency, by decreasing the conductor temperature margin. Inability to remove the operational heating sources.</p> <p>2) Degrade/destroy cryostat vacuum which results in increased refrigeration load, eventual TPX downtime.</p> <p>3) He may accumulate within the confines of the TF lead box, arcing may occur (Paschen curve minimum), given a simultaneous insulation breakdown.</p>	<p>1) Increased quenching.</p> <p>2) Flow meter/ pressure gauge may detect.</p> <p>3) Arcing.</p> <p>4) Vacuum pressure gauge.</p>	None		C	II	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) Weld qualification and welder certification per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD33A\A Subsystem Name: Lead Box Internal Assy Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Incorrect reading	<p>1) Component failure.</p> <p>2) Instrumentation out of calibration.</p> <p>3) Pressure oscillations in plumbing.</p> <p>4) Impurity material buildup in flow sensor leading to incorrect readings.</p> <p>5) Erosion.</p> <p>Cause 4 & 5 due to particulate such as weld slag, grinding dust, corrosion, Cr (the coil Cr plating could, in time, crack and flake. The outlet flowmeters would be more susceptible).</p>	<p>1) Failure to detect quench by this quench detection circuit on adjacent double pancakes; if normal zone undetected by other techniques, resultant damage to magnet.</p> <p>2) False indication of quench will be ignored by system if other techniques do not sense quenching of coils.</p>	<p>1) Transient or erratic reading.</p> <p>2) Persistent incorrect reading.</p> <p>3) TPX instrumentation software could detect problem by setting upper and lower bounds of correct operation.</p>	<p>1) Calibration.</p> <p>2) Replace marginal units at earliest convenience.</p>		C	IV	<p>1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits.</p> <p>2) Cleanliness control during assembly/storage.</p> <p>3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) TPX project has responsibility for adequate purging of the system.</p> <p>5) TPX project to monitor He quality from TF refrigeration system.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD33A\b Subsystem Name: Lead Box Internal Assy Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Pressure sensing tubing blockage (if sensor of this type)	1) Foreign object (weld slag, grinding dust, corrosion, Cr flakes) or He impurity.	Inaccurate or no flow reading. Loss of this quench detection circuit on adjacent double pancakes; if normal zone undetected by other techniques, resultant damage to magnet.	Persistent incorrect reading.	None		C	IV	1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits. 2) Cleanliness control during assembly/storage. 3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) TPX project has responsibility for adequate purging of the system. 5) TPX project to monitor He quality from TF refrigeration system.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD33C\ Subsystem Name: Lead Box Internal Assy Component Name: Helium filter		Function: Prevent the potential carry over of solid contaminants which may be present in the He lines into, or throughout, the TF Magnet Assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Partial Blockage	1) Particulate such as: weld slag, grinding dust, corrosion, solder balls. 2) Failure to dry (evacuate) He subsystem adequately prior to cool down. 3) Solids (i.e., ice) originating from leaks in the refrigeration system.	Insufficient coolant flow leading to localized heating and quench.	1) Flow or pressure sensor may detect. 2) Quench detection system.	Renewal cycle		C	IV	1) Cryogenic system particulate is typically not of the type that tend to plug filters (i.e., mud or slurry consistency). 2) The filter has been designed to provide adequate flow at 10% of the available area. 3) Attention to house keeping/cleanliness during manufacturing, TPX assembly. 4) Pre-filtering is done by filters located in refrigeration system. Contamination source may be limited to piping coming from the filters into the cryostat, including all He lines inside the cryostat.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD33C\b Subsystem Name: Lead Box Internal Assy Component Name: Helium filter		Function: Prevent the potential carry over of solid contaminants which may be present in the He lines into, or throughout, the TF Magnet Assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Unable to prevent contamination passage.	<p>1) Defective or damaged component. Ruptured sinter bronze (or stainless steel) filtering element.</p> <p>2) Particulate too small for filter to intercept.</p> <p>3) Oil.</p> <p>4) Contamination present in He lines changes to liquid/gaseous state during system warm-up, passes through filter, and contaminates system (e.g., ice-water-ice).</p>	<p>1) Passage of particulate material can potentially cause He flow blockage in the coils, or in the small entrance area in the CICC.</p> <p>(Shorts, if contamination facilitates electrical path through He in line insulators - this is addressed in TFQD32C).</p>	<p>1) Flow meters may detect condition.</p> <p>2) Coil to ground short.</p>	None.		D	III	<p>1) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>2) Ensure component not damaged during weld process.</p> <p>3) Pre-filtering is done by filters located in refrigeration system. Contamination source may be limited to piping coming from the filters into the cryostat, including all He lines inside the cryostat.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD33D\A Subsystem Name: Lead Box Internal Assy Component Name: Insulation.		Function: Provide electrical/thermal insulation between the TF lead box and the coil leads.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Coil lead-to-Lead box insulation failure.	1) Short due to material defects; voids, cracks, etc. 2) Damage during installation. 3) Damage due to cyclic thermal (CTEs) and magnetic stresses. 4) Long term radiation degradation.	1) If the insulation/ground wrap around the leads is good, it may not be a problem. (If the insulation/ground wrap around the leads also fails, a short to the lead box causing major damage to the coil and surrounding structures.)	Loss of TF magnet system operation.	None		D	III	1) Insulation (G10) qualified for cryogenic/radiation operation. 2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c. 3) Insulation testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. 4) Proper assembly procedures will be developed in Phase II.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD33D\b Subsystem Name: Lead Box Internal Assy Component Name: Insulation.		Function: Provide support and thermal/electrical (from eddy currents) insulation between the TF lead box and the He lines within the TF lead box walls.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He lines-to-Lead Box insulation failure.	1) Short due to material defects; voids, cracks, etc. 2) Damage during installation. 3) Damage due to cyclic thermal (CTEs) and magnetic stresses. 4) Long term radiation degradation.	1) Thermal/electrical short to TF lead box. Eddy current flow into the He manifold. 2) Degraded support function.	None.	None. Inspect while access is available to TF lead box internal components.		C	IV	1) Insulation (G10) qualified for cryogenic/radiation operation. 2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c. 3) Proper assembly procedures will be developed in Phase II.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET

Failure Modes, Effects, and Criticality Analysis

Item No. TFQD4/b Subsystem Name: Octant Assy Component Name: Structure		Function: Provide structural support and alignment to the TF coil and other TF magnet system components, as well as the PF coils.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	1) Operational overstress due to: a) In plane burst pressure directed radially outboard. b) Non-uniform burst pressure (directed inboard toward the center of the Tokamak) produced by Lorentz force. c) Out of plane loads from PF coils. d) Thermal stresses. e) Quench loads. f) Seismic loads. 2) Fatigue 3) Weld failure. 4) Defect in base material.	1) Distortion of case leading to TF coil misalignments, distortion of TF magnetic field distortion, quench. 2) Cracking or deformation/misalignment of case/components leading to structural/electrical failure.	1) Weld inspection. 2) NDT. 3) Alignment check. 4) Inability to initiate or sustain plasma.	1) TF structural alignment check should be performed whenever possible to detect this and other misalignment causes. 2) Visual inspection of the welds that are accessible. 3) NDT.		D	II	1) Conservative structural design through load analysis required by the SCDC. The ICD s also detail the allowable loads to the structure. 2) Radially outboard loads reacted by tying outboard legs together with an inter-coil structure. 3) Wedging loads reacted by hoop compression in nose sections. 4) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001.
(continues ...)								

Item No. TFQD4b (Cont)	Function: Provide structural support and alignment to the TF coil and other TF magnet system components, as well as the PF coils.
Subsystem Name: Octant Assy	
Component Name: Structure	

Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Structural failure)								Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP.
								5) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.
								6) NDT for welds: "Material & Component Test Plan", TPX-PLAN-MCTP, "Coil Verification Test Plan", TPX-PLAN-VTP, "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD41/a Subsystem Name: Intercoil structure Component Name: Grounding		Function: Provides grounding for the eddy current flow induced in the octant structures.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Open	1) Damage to grounding strap during quadrant assembly or handling. 2) Damage during cyclic operation. 3) Cold joint or cracks, aggravated by thermal cycling. 4) CTE of the materials.	Increased Eddy current flow in the structure, added refrigeration system load due to increased thermic generation.	1) After TF magnet system installation or upon a TPX maintenance action, test as part of system checkout procedure. 2) Operation, excessive quenching of a quadrant due to heat load.	None.		C	IV	Tested during the final assembly checkout procedure per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42\A Subsystem Name: Octant Assy (Structure) Component Name: Coil Case Assy		Function: This is a main structural member providing structural support and alignment to the coil, the TF magnet system, and the PF coils. It also provides for an additional thermal barrier for the TF coils by intercepting case heating at the nose section through the use of case cooling lines.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Weld failure	1) Assembly error. 2) Crack prone location due to contaminants in weld area. 3) Improper prep. 4) Nitrogen bubble formation around the welded joint during welding. 5) Material fatigue. 6) Failure from stresses arising from structure 316LN and Inconel 625 weld material CTE's.	1) Potential loss of the TF structure integrity causing increased strain on other structural members, including the PF coils. Cracking or deformation of case. 2) Contributor to misalignments, quench, increased disruptions. 3) Potential increased structural stresses in the coil.	1) Weld inspection after assembly. 2) Non destructive testing (NDT). 3) Quenching during operation or plasma initiation. 4) Depending on where they are located, the strain gages may be able to detect an increased loading on the structure.	1) Visual inspection of the welds that are accessible. 2) NDT.		D	II	1) Cleanliness requirements per TF Welding Procedure, TBD. 2) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. (The use of Inconel 625 will mitigate the distortion issue. B&W has design and manufacturing experience [and patents] on welding processes utilizing this material).

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42/c Subsystem Name: TF Octant Assy Component Name: Coil Case Assy		Function: This is a main structural member providing structural support and alignment to the coil, the TF magnet system, and the PF coils. It also provides for an additional thermal barrier for the TF coils by intercepting case heating at the nose section through the use of cooling lines.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Misalignment	1) Assembly error. 2) Distortion from welding. 3) Long term movement of structures due to relaxation of residual stresses from welding. 4) Long term movement of structures due to relaxation of stresses arising from structure 316LN and Inconel 625 weld material CTE's. 5) Long term movement of structures due to operational forces. 6) Thermally induced movements.	1) Failure to meet error field and ripple requirements which in turn will reduce the confinement capability of the tokamak unless correctable by error field coils. 2) If FEC coils are unable to compensate and control the thresholds for locked modes, this will result in increased incidences of disruptions.	1) TF field distortion, increased quench incidences. 2) Increased plasma disruption incidences.	1) TF Magnet system alignment check should be performed whenever possible.		C	II	Aggregate errors amongst coils must be less than 1mm: 1) Proper procedures to correct alignment problems will be developed in Phase II. 2) Multiple alignment checks of the coil against fiducials will be performed during assembly per TF Case Assembly Procedure OP TPX-00004. 3) Weld qualification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42\c (Cont) Subsystem Name: Octant Assy (Structure) Component Name: Coil Case Assy		Function: This is a main structural member providing structural support and alignment to the coil, the TF magnet system, and the PF coils. It also provides for an additional thermal barrier for the TF coils by intercepting case heating at the nose section through the use of cooling lines.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Misalignment)								<p>(The use of Inconel 625 will mitigate the distortion issue. B&W has design and manufacturing experience [and patents] on welding processes utilizing this material).</p> <p>4) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42Aa Subsystem Name: TF Coil Case Assembly Component Name: Case Loop (Cooling)		Function: Adds thermal capability to cold mass and reduce peak temperatures during a pulse.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He leak	1) Weld failure caused by assembly error, contaminated weld area, or fatigue due to thermal, quenching, magnetic, plasma disruption or seismic cycles. 2) Tubing fatigue. 3) Overpressure during quench event. 4) Weakness in parent material.	1) Increased load on refrigeration system 2) Failure to maintain portions of coil adequately cool, leading to quench. 3) Cryostat vacuum degradation/destruction. 3) He may accumulate within the confines of the TF lead box, arcing may occur (Paschen curve minimum), given a simultaneous insulation breakdown.	1) Quench monitoring. 2) Coolant flowmeter or pressure sensor may detect condition.	None		D	II	1) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. (The use of Inconel 625 will mitigate the distortion issue. B&W has design and manufacturing experience [and patents] on welding processes utilizing this material).
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42A1a (Cont) Subsystem Name: TF Coil Case Assembly Component Name: Case Loop (Cooling)		Function: Adds thermal capability to cold mass and reduce peak temperatures during a pulse.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: He leak)								<p>2) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>3) Insulation testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>4) TPX Project should monitor instrumentation data during operation.</p> <p>5) TPX Project should consider cryostat vacuum/ pressure gauge.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42B/a Subsystem Name: TF Coil Case Assembly Component Name: CS Attachment Lug		Function: Provide mechanical support and alignment for the PF Magnet System Central Solenoid (CS) Assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	1) Weld failure or distortion. 2) Assembly error. 3) Nitrogen bubble formation around the welded joint during welding. 4) Crack prone location due to contaminants in weld area. 5) From stresses arising from structure 316LN and Inconel 625 weld material CTE's. 6) Material fatigue.	1) Unable to provide adequate CS structural support. 2) Misalignment problems, CS magnetic field distortion. 3) CS coils quench. 3) Damage to structural integrity of the CS magnet. 4) CS magnet unable to support the plasma initiation.	1) Weld inspection. 2) NDT. 3) Alignment check. 4) CS coils quenching.	None.		D	II	1) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. (The use of Inconel 625 will mitigate the distortion issue. B&W has design and manufacturing experience [and patents] on welding processes utilizing this material). 2) Cleanliness requirements per TF Welding Procedure, TBD.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42B/a Subsystem Name: TF Coil Case Assembly Component Name: CS Attachment Lug		Function: Provide mechanical support and alignment for the PF Magnet System Central Solenoid Assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Structural failure)	<p>7) Operational overstress due to:</p> <p>a) In plane burst pressure directed radially outboard.</p> <p>b) Non-uniform burst pressure (directed inboard toward the center of the Tokamak) produced by Lorentz force.</p> <p>c) Out of plane loads from PF coils.</p> <p>d) Thermal stresses.</p> <p>e) Quench loads.</p> <p>f) Seismic loads.</p>							

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42C/a Subsystem Name: TF Coil Case Assembly Component Name: PF5, PF6 and PF7 Mount		Function: Interface which provides support to the PF5, PF6 and PF7 coils. The interface experiences differential radial movement between the PF coil and the TF structure during temperature changes. The upper PF5 and PF6 mounts also serve as an attachment point for the TF magnet handling system. The lower PF5 mount can serve as a TF magnet assembly aid, by providing temporary support of the TF nose.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	1) Weld failure or distortion. 2) Material fatigue. 3) Assembly error. 4) Nitrogen bubble formation around the welded joint during welding. 5) Overstress during the transportation/installation process (Vacuum Vessel will be supported off of the TF Octants during their installation).	1) Unable to provide adequate PF structural support. 2) Misalignment problems, PF magnetic field distortion. 3) Damage to structural integrity of the PF magnet. 4) PF magnet unable to support the plasma initiation. 5) Insulation damage leading to PF magnet short to TF structure.	1) Weld inspection. 2) NDT. 3) Alignment check. 4) Inability to initiate or sustain plasma.	1) TF structural alignment check should be performed whenever possible to detect this and other misalignment causes. 2) Visual inspection of the welds that are accessible. 3) NDT.		D	II	1) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. 2) Visual inspection of welds/joint.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42C\A (Cont) Subsystem Name: TF Coil Case Assembly Component Name: PF5, PF6 and PF7 Mount		Function: Interface which provides support to the PF5, PF6 and PF7 coils. The interface experiences differential radial movement between the PF coil and the TF structure during temperature changes. The upper PF5 and PF6 mounts also serve as an attachment point for the TF magnet handling system. The lower PF5 mount can serve as a TF magnet assembly aid, by providing temporary support of the TF nose.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Structural failure)								3) NDT for welds: "Material & Component Test Plan", TPX-PLAN-MCTP, "Coil Verification Test Plan", TPX-PLAN-VTP, "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) Proper TF handling and installation procedures must be developed in Phase II.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET

Item No. TFQD42Cb		Function: Interfaces which provide support to the PF5, PF6 and PF7 coils. The interface experiences differential radial movement between the PF coil and the TF structure during temperature changes. The upper PF5 and PF6 mounts also serve as attachment points for the TF magnet handling system. The lower PF5 mount can serve as a TF magnet assembly aid, by providing temporary support of the TF nose.						
Subsystem Name: TF Coil Case Assembly								
Component Name: PF5, PF6 and PF7 Mount								
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Misalignments of the PF coils due to the mounts. (continues...)	This will be the result of overall TF Magnet Assembly misalignments caused by: 1) Misalignments at TPX during octant to octant assembly. 2) Distortion from welding. 3) Crack prone location due to contaminants in weld area. 4) Long term movement of structures due to relaxation of residual stresses from welding. 5) Long term movement of structures due to relaxation of stresses arising from structure 316LN and Inconel 625 weld material CTE's.	Increase in PF field error.	PF magnetic field distortion.	Structural alignment check should be performed whenever possible to detect this and other misalignment causes.		D	III	1) Proper alignment procedures will be developed in Phase II. 2) Cleanliness requirements per TF Welding Procedure, TBD. 3) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. The use of Inconel 625 will mitigate the distortion issue.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD42C\b (Cont) Subsystem Name: TF Coil Case Assembly Component Name: PF5, PF6 and PF7 Mount		Function: Interfaces which provide support to the PF5, PF6 and PF7 coils. The interface experiences differential radial movement between the PF coil and the TF structure during temperature changes. The upper PF5 and PF6 mounts also serve as an attachment points for the TF magnet handling system. The lower PF5 mount can serve as a TF magnet assembly aid, by providing temporary support of the TF nose.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Misalignments of the PF coils due to the mounts.)	6) Tension bolts at E.C. Break not properly tightened at installation or become loose during cyclic operation.							4) Visual inspection of welds. 5) Current design calls for the use of a Superbolt (a manual tensioning bolt). 6) The B&W TF structural design has alignment features throughout the toroid's EC break joint area. The fiducialization of the octants will aid in alignments performed at TPX assembly. 7) WEC has responsibility of designing appropriate alignment provisions for the PF Coils.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No.: TFQD43a Subsystem Name: Octant Assy (Structure) Component Name: Intercoil Structure (Top & Bottom)		Function: Provides location and structural support for TF coil cases.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	Caused by weld failure due to: 1) Assembly error. 2) Improper prep. 3) Crack prone location due to contaminants in weld area. 4) Nitrogen bubble formation around the welded joint during welding. 5) Material fatigue. 6) Failure from stresses arising from structure 316LN and Inconel 625 weld material CTE's. 7) Over turning loads.	1) Potential loss of the TF structure integrity causing increased strain on other structural members. 2) Misalignments, quench. 3) Potential increased structural stresses at the PF coil interfaces.	1) Weld inspection after assembly. 2) Non destructive testing (NDT). 3) Quenching during operation or plasma initiation. 4) Depending on where they are located, the strain gages may be able to detect an increased loading on the structure.	1) Visual inspection of the welds that are accessible. 2) NDT.		D	III	1) Cleanliness requirements per TF Welding Procedure, TBD. 2) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. (The use of Inconel 625 will mitigate the distortion issue. B&W has design and manufacturing experience on welding processes utilizing this material).

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No.: TFQD43/b Subsystem Name: Octant Assy (Structure) Component Name: Intercoil Structure (Top & Bottom)		Function: Provides location and structural support for TF coil cases						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Misalignment	1) Distortion from welding. 2) Long term movement due to relaxation of residual stresses from welding. 3) Long term movement due to relaxation of stresses arising from structure 316LN and Inconel 625 weld material CTE's. 4) Misalignments due to shipping/installation loads (Vacuum Vessel will be supported off of the TF Octants during their installation).	1) Failure to meet error field and ripple requirements which in turn will reduce the confinement capability of the tokamak unless correctable by field error coils. 2) Increased structural stresses at the PF coil interfaces. 3) PF field error increased. 4) Increased incidences of plasma disruptions. 5) FECC coil misalignments. 6) Structural stress distribution altered.	1) Alignment check. 2) Inability to initiate or sustain plasma. 3) Strain gages can detect??	1) TF structural alignment check should be performed whenever possible to detect this and other misalignment causes.		D	II	1) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. 2) Proper TF handling and installation and alignment procedures will be developed in Phase II.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD43Ba Subsystem Name: Intercoil structure Component Name: Bolted Joint Assy (Upper & Lower)		Function: A structural member which provides for the transmission of mechanical loads between octants, while providing insulation to control or prevent net eddy current flow in the toroid.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	1) Material/Component fatigue 2) Tension bolts not properly tightened at installation. 3) Shear keys (if used) unable to properly accommodate cyclic thermal/magnetic environment in the joint. 4) Bolts come loose due to thermal/magnetic cyclic operation. 5) CTE's not properly matched to maintain required tension on bolts.	1) Failure to meet error field and ripple requirements which in turn will reduce the confinement capability of the tokamak unless correctable by error field coils. 2) E.C. Break insulation degradation or failure due to inability to keep the necessary compression on the joint, and no shear stresses. 3) Increased structural stresses at the PF coil interfaces.	1) TPX toroidal field distortion, quench. 2) Increased heat load due to eddy currents through damaged insulation.	Verify proper torque when possible.		D	II	1) SCDC requires conservative structural design. Current modeling efforts are underway to ensure the joint is maintained under the necessary compression during the thermal cycles. Further design effort is required in Phase II. Life testing should be kept open as an option for verification if needed. 2) Current design calls for the use of a Superbolt (a manual tensioning bolt).
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD43B\A Subsystem Name: Intercoil structure Component Name: Bolted Joint Assy (Upper & Lower)		Function: A structural member which provides for the transmission of mechanical loads between octants, while providing insulation to control or prevent net eddy current flow in the toroid.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Structural failure)	6) Operational overstress due to: a) In plane burst pressure directed radially outboard. b) Non-uniform burst pressure (directed inboard toward the center of the Tokamak) produced by Lorentz force. c) Out of plane loads from PF coils. d) Thermal stresses. e) Quench loads. f) Seismic loads.							

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD43Bb Subsystem Name: Intercoil structure Component Name: Bolted Joint Assy (Upper & Lower)		Function: A structural member which provides for the transmission of mechanical loads between octants, while providing insulation to control or prevent net eddy current flow in the toroid.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrical short	1) Damage to insulation during quadrant assembly or handling. 2) Damage during cyclic operation due to foreign objects/uncleanliness. 3) Voids/cracks/defects/contamination on insulating material present at assembly, or appearing latter on, and aggravated by thermal/magnetic cycling. 4) CTE of the materials. 5) Life limiting events on the material; loads due to installation, thermal/magnetic cycles, seismic events.	1) Eddy current flow through the E.C. Break, added refrigeration system load due to increased thermic generation. 2) Difficulty in plasma start up.	1) After quadrant assembly, test for 1kV voltage standoff. 2) After TF magnet system installation or upon a TPX maintenance action, test as part of system checkout procedure. 3) Operation, excessive quenching of a quadrant due to heat load.	None. Unless periodic replacement due to limited life determination.		C	III	1) Insulation (G10) qualified for cryogenic /radiation operation. 2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c. 3) Manufacturing will ensure removal of all surface particulate. 4) Proper quadrant assembly and alignment procedures will be developed in Phase II.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD43B\b (Cont) Subsystem Name: Intercoil structure Component Name: Bolted Joint Assy (Upper & Lower)		Function: A structural member which provides for the transmission of mechanical loads between octants, while providing insulation to control or prevent net eddy current flow in the toroid.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Electrical short)	6) Long term radiation degradation. 7) Stresses produced by misalignments. 8) Arcing along the edges of materials (surface tracking) especially at fasteners. 9) Bridging of insulation by another component (e.g. support system, debris, superinsulation).							

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD43C/a Subsystem Name: Intercoil Structure Component Name: ICS Cooling		Function: Adds thermal capability to the coils, by reducing the thermal flow of heat intercepted/generated in the intercoil structure.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He leak	1) Weld failure caused by assembly error, contaminated weld area, or fatigue due to thermal, quenching, magnetic, plasma disruption or seismic cycles. 2) Tubing fatigue. 3) Overpressure during quench event. 4) Weakness in parent material.	1) Increased load on refrigeration system 2) Failure to maintain coil adequately cool, leading to quench. 3) Cryostat vacuum degradation/destruction.	1) Quench monitoring. 2) Coolant flowmeter or pressure sensor may detect condition.	None		C	III	1) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. (The use of Inconel 625 will mitigate the distortion issue. B&W has design and manufacturing experience [and patents] on welding processes utilizing this material).
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD43C\la (Cont) Subsystem Name: Intercoil Structure Component Name: ICS Cooling		Function: Adds thermal capability to the coils, by reducing the thermal flow of heat intercepted/generated in the intercoil structure.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: He leak)								<p>2) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>3) TPX Project should monitor instrumentation data during operation.</p> <p>4) TPX Project should consider cryostat vacuum/ pressure gauge.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET

Item No. TFQD45C/a Subsystem Name: Intercoil Structure Component Name: FEC Coil Supports		Function: Provides mechanical support to the Field Error Correction Coils (FECC). There is limited thermal flow across these interfaces.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Misalignments of the FECC due to the supports. (continues...)	This will be the result of overall quadrant misalignments caused by: 1) Misalignments at TPX during octant to octant assembly. 2) Distortion from welding. 3) Crack prone location due to contaminants in weld area. 4) Long term movement of structures due to relaxation of residual stresses from welding. 5) Long term movement of structures due to relaxation of stresses arising from structure 316LN and Inconel 625 weld material CTE's.	1) FEC coils unable to compensate for TF system misalignments or eccentricities, resulting in failure to meet error field and ripple requirements which in turn will reduce the confinement capability of the tokamak. 2) FEC coils unable to control the thresholds for locked modes, resulting in increased incidences of disruptions.	1) TF field distortion, increased quench incidences. 2) Increased plasma disruption incidences.	1) FEC coils/TF Magnet system alignment check should be performed whenever convenient.		D	III	1) Develop/qualify proper procedures for structural alignment in Phase II. B&W fiducialization of the octants will aid in this procedure. 2) Cleanliness requirements per TF Welding Procedure, TBD. 3) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. (The use of

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD45C/a (Cont) Subsystem Name: Intercoil Structure Component Name: FEC Coil Supports		Function: Provides mechanical support to the Field Error Correction Coils (FECC). There is limited thermal flow across these interfaces.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Misalignments of the FECC due to the supports)	6) Tension bolts at E.C. Break not properly tightened at installation or become loose during cyclic operation.							<p>Inconel 625 will mitigate the distortion issue. B&W has design and manufacturing experience [and patents] on welding processes utilizing this material).</p> <p>4) Visual inspection of welds.</p> <p>5) Current design calls for the use of a Superbolt (a manual tensioning bolt).</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD45E\ Subsystem Name: TF Octant Assembly Component Name: TF Support Bracket		Function: Provide the intercoil structure with a guide pin/slot assembly to aid in the TF Magnet Assembly alignment during assembly and to maintain the alignment during thermal cycling (no net toroidal movement of the structure due to thermal cycling).						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Weld failure	1) Contaminant in weld joint. 2) Assembly error. 3) Nitrogen bubble formation around the welded joint. 4) Material fatigue.	1) The bracket's ability to maintain the necessary alignment of the structure during thermal cycling can be severely impaired, forces on the octant will be reacted by the intercoil structure, coil case, and structural joints (E.C. Break). 2) If the other structures are unable to react the forces, failure to meet error field and ripple requirements which in turn will reduce the confinement capability of the tokamak unless correctable by field error coils.	1) Weld inspection after assembly. 2) NDT. 3) Depending on where they are located, the strain gages may be able to detect an increased loading on the structure when a weld degrades.	1) TF structural alignment check should be performed whenever possible to detect this and other misalignment causes. 2) Visual inspection of the welds that are accessible. 3) NDT.		D	II	1) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. 2) NDT for welds: "Material & Component Test Plan", TPX-PLAN-MCTP, "Coil Verification Test Plan", TPX-PLAN-VTP, "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD45E\1a (Cont) Subsystem Name: TF Octant Assembly Component Name: TF Support Bracket		Function: Provide the intercoil structure with a guide pin/slot assembly to aid in the TF Magnet Assembly alignment during assembly and to maintain the alignment during thermal cycling (no net toroidal movement of the structure due to thermal cycling).						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(Continued: Weld failure)								3) Visual inspection of welds. 4) Cleanliness requirements per TF Welding Procedure, TBD.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD46/a Subsystem Name: Instrumentation Component Name: Strain gauges		Function: To measure the response of the TF magnet structure to the tokamak operating environment. At approximately 100 locations, these will measure structural response information to validate design analyses and obtain peak stress levels in the magnet structure.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Open	1) Defective gauge. 2) Damaged component at assembly. 3) Fatigue of gauge. 4) Fatigue of leads.	Loss of structural response information until standby unit is brought up into operation. If the standby unit also fails, the information will be lost for that structural element location.	Signal lost	1) Replace non-functional units, at the earliest convenience. 2) Recommend periodic test of standby unit.		C	IV	1) Test during TF Magnet System final assembly and checkout per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 2) Each location will have redundant standby strain gages which can be connected when primary fails.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD46b Subsystem Name: Instrumentation Component Name: Strain gauges		Function: To measure the response of the TF magnet structure to the tokamak operating environment. At approximately 100 locations, these will measure structural response information to validate design analyses and obtain peak stress levels in the magnet structure.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Short	1) Defective gage. 2) Damaged component at assembly. 3) Long term radiation degradation of the carrier matrix or wire insulation.	Loss of structural response information until standby unit is brought up into operation. If the standby unit also fails, the information will be lost for that structural element location.	Signal loss or noise.	1) Replace non-functional units/wires, at the earliest convenience. 2) Recommend periodic test of standby unit. 3) If carrier matrix or wire insulation have limited life, replace at scheduled intervals.		C	IV	1) Test during TF Magnet System final assembly and checkout per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 2) Each location will have redundant standby strain gages which can be connected when primary fails. 3) Strain gages carrier matrix and wire insulation to be cryogenic/radiation environment qualified. Details in phase II.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD46c Subsystem Name: Instrumentation Component Name: Strain gauges		Function: To measure the response of the TF magnet structure to the tokamak operating environment. At approximately 100 locations, these will measure structural response information to validate design analyses and obtain peak stress levels in the magnet structure.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Incorrect reading or measurement drift.	<p>1) Instrumentation out of calibration.</p> <p>2) Carrier matrix or adhesive are not transmitting the strains to the strain gage grid (if of this type), due to long term temperature cycling/radiation degradation.</p> <p>3) Other error sources such as: Temperature effects, electrical noise, thermally or magnetically induced voltages, resulting from TPX operation.</p>	Unreliable data being gathered, therefore, loss of structural response information.	<p>1) Operational data analysis may reveal the problem.</p> <p>2) Comparison between the outputs of the primary and standby units could be performed as a check.</p>	<p>1) Visual inspections of adhesive integrity.</p> <p>2) Regularly scheduled instrumentation calibrations.</p> <p>3) Replace non-functional units/wires, at the earliest convenience.</p> <p>4) Periodic test of standby unit.</p> <p>5) If carrier matrix, wire insulation, or adhesive have limited life, replace at scheduled intervals.</p>		B	IV	<p>1) PPPL to perform regular calibrations of instrumentation.</p> <p>2) Engineering should evaluate the need for shielded leads and wires to prevent electrical noise in Phase II.</p> <p>3) Engineering should evaluate the need to require twisted wires to mitigate magnetic induction in Phase II.</p> <p>4) Strain gages carrier matrix, wire insulation, and adhesive, to be cryogenic/radiation environment qualified. Details in Phase II.</p>

APPENDIX B

FMECA Unique Reference Identifiers

REFERENCE IDENTIFIERS

TF Magnet System	T
TF Magnet Assembly	TF
TF Quadrant	TFQ
E.C.Break (at Inner Leg)	TFQA
Intermodule Splice Joint	TFQB
He Isolator	TFQB1
Quench Sensor - Flow Meters	TFQB2
He Lines	TFQB3
Module to Buss Joint	TFQC
He Isolator	TFQC1
Quench Sensor - Flow Meters	TFQC2
Quench Sensor - Cable Instrumentation	TFQC3
TF Octant	TFQD
Coil Potting in Case	TFQD1
Winding Pack Assembly	TFQD2
Grounding	TFQD21
Cable (CICC)	TFQD22A
Superconductor	TFQD22A1
Conduit	TFQD22A2
Quench Sensor - Non-Inductive Voltage Tap	TFQD22A3
Quench Sensor - Fiber Optics	TFQD22A4
He Stub	TFQD22B
Insulation	TFQD24
TF Lead Box	TFQD3
Coil to Coil Splice Joint	TFQD31
He Isolator	TFQD31A
Quench Sensor - Flow Meters	TFQD31B
Quench Sensor - Cable Instrumentation	TFQD31C
Coil Plumbing	TFQD32
He lines	TFQD32A
He Isolator	TFQD32C
Lead Box Components	TFQD33
Quench Sensor - Flow Meters	TFQD33A
Filter	TFQD33C
Insulation	TFQD33D
Structure	TFQD4
Grounding	TFQD41
Coil Case	TFQD42
Case Loop (Cooling)	TFQD42A
CS Mount	TFQD42B
PF5, PF6 & PF7 Mount	TFQD42C
Intercoil Structure	TFQD43
Bolted Conn./E.C. Break (at Outer Leg)	TFQD43B
Intercoil Cooling	TFQD43C
Interfaces	TFQD45
TF Quadrant Support (at Outer Leg)	TFQD45A
Seismic Snubber Interface	TFQD45B
FEC Coils Interface	TFQD45C
TF Support at Nose (Temp.)	TFQD45D
TF Support Bracket	TFQD45E
Strain Gages	TFQD46

B-3 COIL REACTION PRELIMINARY PROCEDURES

ACCELERATOR AND MAGNET SYSTEMS	TF COIL REACTION PROCEDURE	OP TPX-00002 08/02/95 Rev. 00
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SCOPE

This procedure establishes the method for reaction of the Toroidal Field (TF) superconducting magnet coils for the Tokamak Physics Experiment (TPX) for Princeton University. The equipment is described in details in the document "Reaction Furnace Specifications" and will be mentioned here only as a reference as it relates to the operating procedures.

The scope of the reaction operational procedure follows the winding procedure scope of work and precedes the insulation and VPI / Curing operational procedure.

GENERAL NOTES

1. For information regarding safety and proper use of any applicable chemicals, consult the Material Safety Data Sheet (MSDS). These sheets are available from the foreman.
2. All chemicals, when not in use, are to be stored in an approved storage container.
3. All waste (i.e. rags, chemicals, etc.) are to be disposed of properly, in accordance with company policies.
4. Safety equipment (i.e. gloves, safety glasses, coveralls, etc.) are to be worn when applicable.
5. Precautions are to be taken to maintain the cleanliness of the environment and individual parts. Coils should be covered during idle periods. Lint-free gloves should be worn when handling the conductor to avoid leaving fingerprints.
6. If any unusual conditions are observed, immediately contact the supervisor.

PURPOSE

The purpose of this operational procedure is to assure the operators actions are compatible with the reaction system features and to provide guidance for the operator(s). In order to establish a comprehensive operational procedure, consistency must be maintained with regard to:

- Equipment
- Materials and auxiliary objects
- Performance requirements
- Processes

ORIGINATOR: Peter Rackov	DOC ID: 13-950727-BW-PRackov-03	DATE: 8/2/95
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SUPPORTING DOCUMENTS

The following documents form an integral part of the TF Coil Reaction Procedure:

Document Name	Document Number
TF Coil Design Drawing	(TBD)
Reaction Furnace Specification	TPX-SPEC-133-0003
Material Handling Procedure	(TBD)
MITAP	(TBD)
General QC Procedure	(TBD)

MATERIAL AND AUXILIARY EQUIPMENT

1. Wound TF Coil (Part No. TBD)

The object of heat treatment and reaction will be the conductor wound into a "D" shape coil. The conductor consists of an Incoloy 908 conduit, encasing the unreacted combination of copper, tin and niobium in the form of a cable.

2. Pressure Gages

These gages will be used to measure vacuum in the furnace and the partial pressure of argon. The pressure gages will be electrically heated filament type.

3. Thermocouples

The thermocouples will be "K" type and will measure the temperature distribution on the surface of the coil mounted in its frame.

4. Helium Gas

Commercial grade helium will be used to detect any leaks in the oven. Purified helium will be used to purge the conduit, so that only traces of water and oxygen (less than 0.1 ppm each) will be measured at the inlet to the conduit.

5. Argon Gas

The primary function of the argon introduction into the furnace, at a particular partial pressure, is to facilitate the heat transfer between the heaters and the coil, by convection. The same heat transfer mechanism will be used in cooling down the coil(s).

PERFORMANCE REQUIREMENTS

1. Reaction Scenario A

The temperature-time diagram of this scenario is given in Figure 1 of this document. The temperature margin at plateaus is $\pm 5^{\circ}\text{C}$.

2. Reaction Scenario B

The temperature-time diagram of this scenario is given in Figure 2. of this document. The temperature margin at the plateau is $\pm 5^{\circ}\text{C}$.

OPERATING PROCEDURE

1. Issue released wound TF Coil

2. Verify that the coil is wound on the coil form / frame, including the incorporation of the dimensional spacers. Next, check that the coil has been fastened to the coil form / frame, which serves as tooling to maintain coil integrity. Confirm that the helium stub tubes have been leak checked.
3. Using the overhead crane, mount the coil form and the coil on the loading (transfer) cart. Anchor the coil form to the cart base.
4. Install the lead supports. Install the internal purge manifold(s) to the coil. Mount the thermocouples on the surface of the coil and the tooling.
5. Roll the cart with the coil into the furnace. Anchor the wheels of the cart to the structural base plate in the furnace.
6. Connect and check the purge manifold to the purge system interface. Connect and check the thermocouples to the thermocouple interface.
7. Close and latch the furnace door.
8. Turn on the power and boot up the computer. Prior to initiating a furnace run, log in the following information:
 - Run number
 - Operator name
 - Date and time
 - Component identification

9. Check to confirm that the following controls are properly set at the operator console:
 - Program designation
 - Vacuum system auto initiation
 - Leak check switch and readout
 - Program interrupt
 - Manual temperature set
 - Alarm indications and resets
10. Have the supervisor verify the loading of the correct operating and data logging programs and execute any required supervisory level entries to the program.
11. Check to confirm that the following closed loop control sensors and parameters are monitored, recorded and serviceable:
 - Control program set point
 - Furnace zone control thermocouple temperatures
 - Charge mounted thermocouple temperatures
 - Partial pressure control
 - Purge system pressure control
 - Furnace wall coolant temperature control
 - Argon contamination level at furnace inlet for partial pressurization system
 - Helium contamination levels: inlet and outlet of the purge system
12. Activate the vacuum system on the console. Evacuate the furnace to a level of 5×10^{-4} Pa (3.8×10^{-6} Torr). At about 1×10^{-5} Torr, the RGA will be turned on.
13. Turn on the helium supply line and pressurize the purge system to 2×10^5 Pa. Check for helium peak on the RGA. If none is detected, proceed. If a leak is detected, repair as necessary.
14. Check helium supply bottles to assure there is adequate helium inventory. Turn on the purified helium purge system and purge the conductor at a flow rate of 10 liters / sec (STD) and a dynamic pressure of 2×10^5 Pa. For a cold coil, the initial reading of impurities at the purge outlet should be less than 100 ppm for oxygen and water each, prior to initiating heating.

15. Check argon supply bottles to assure there is adequate argon inventory. Activate the argon purifying system with impurities readouts. Establish argon flow at 0.25 liters / sec (STD). Adjust the partial pressure of argon to 1×10^2 Pa. Check that the argon supply system delivers argon with the following impurity limits:
 - oxygen: less than 0.1 ppm
 - water: less than 0.1 ppm.
16. Turn on the heaters and heat the coil at 25°C per hour to 185°C , per scenario A (Figure 1, Step A1).
17. Hold the temperature of the coil at $185 \pm 5^\circ\text{C}$ for 120 hours. (Step A2)
18. Continue to heat the furnace at 50°C per hour to 340°C (Step A3), subject to the following constraints:
 - the maximum temperature difference on the surface is not more than 15°C
 - the exhaust from the purge system is less than 0.5 ppm of O_2 and H_2O
19. When the temperature of 340°C has been reached, shut off the argon flow. By using the RGA, verify that there is no helium leak in the purge system. If a leak is detected, turn the furnace off and repair as necessary. The leak detection and turning off the furnace will be under manual control. Turn argon back on. This will accelerate the heat transfer within the coil.
20. Keep the temperature of the coil at $340 \pm 5^\circ\text{C}$ for a minimum of 72 hours (Step A4). If helium leak is detected during this time and if it jeopardizes the vacuum level (3.8×10^{-6} Torr) of the furnace, shut off the purge system. The resulting compromise is that the absence of circulating helium in the conduit will cause a tendency towards temperature gradients across the coil, in the course of further heating of the coil. Thus, the heater power will have to be adjusted to a lower ramp rate. Do not proceed beyond 340°C until the purge system exhaust is below 0.1 ppm for both oxygen and water.
21. Depending of the results of Step A4, use the control system to adjust the heater power to heat the coil to 650°C , at a rate of 75°C per hour (Step A5), subject to a constraint that the maximum temperature difference on the surface must not exceed 15°C . Turn off the partial pressurization system at the start of the ramp to 650°C .
22. Establish a steady state in which heaters keep the temperature of the coil at 650°C for 200 hours (Step A6). In this step, a chemical reaction takes place between Sn and Nb to form an intermetallic compound, Nb_3Sn . Previous purging of the conduit with helium has lowered the percentages of oxygen and water to a level of 0.1 ppm, or less. This virtually eliminates the probability of SAGBO occurrence.

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23. Adjust the power of the heaters so that the coil undergoes cooling at a rate of approximately 25° C per hour, subject to the constraint that the maximum temperature difference on the surface will not exceed 15° C. The vacuum system should maintain the previous level.
 24. Below 450° C, it is expected that the cooldown rate of 25° C per hour could no longer be maintained by radiative cooling in vacuum through the furnace walls alone. Thus, open the valves on the heat exchangers and blow air through them to accelerate the cooldown.
 25. At 350° C, turn on the argon flow at a dynamic partial pressure of 1×10^2 Pa. The presence of argon flow will establish heat exchange with the coil by convection.
 26. Cool down below 50° C in argon atmosphere. Maintain the partial pressure of argon.
 27. Vent the furnace to the atmosphere and remove the reacted coil.

NOTE: For Scenario B, Steps 16-26 temperatures would be adjusted to follow Figure 2.

28. Make sure the process data have been recorded on disk.
29. Turn off the computer. Turn off the power, except the power that keeps the furnace walls warm, by circulating water.

Figure 1. Temperature Cycle Scenario A

Figure 2. Temperature Cycle Scenario B

B-4 REACTION TEMPERATURE UNIFORMITY ANALYSIS

B-4 Reaction Temperature Uniformity Analysis

Temperature uniformity within the coil bundle is necessary to assure consistent Nb₃Sn formation throughout the coil. A model was created to attempt to model the heat transfer conditions within a reaction furnace. Output from the model was compared with matrix heat test results using dummy TF conductor. The computer model was tuned based on the results of the matrix heat treat experiments. The revised model is not capable of predicting temperature uniformity within all coil types due to various operational scenarios. A complete description of the computer model and the matrix heat treatment test results is presented in SDRL 37.

Section C. COIL INSULATION

- C-1. Process Description
- C-2. Insulation Equipment Drawings
- C-3. Cleaning, Insulating, & VPI Preliminary
Procedure

C. COIL INSULATION

C-1. Process Description:

The coil insulation process encompasses the manufacturing steps from the removal of the coils from the reaction furnace to completion of the conductive layer and ground wrap. The chart on the next page summarizes the process. Insulation of the coils is a two step process. The first step is to invert the coil and drop the individual turns, insulating them with Kapton and S2 glass. The turns are lowered into the VPI cavity in which a single layer of S2 glass has been placed and folded out of the way. After placement of all the turns in the cavity the S2 glass is wrapped over the top, the top of the cavity sealed on and the coil vacuum/pressure impregnated. The coil is then removed from the form, cleaned and wrapped with another layer of S2 glass followed by a layer of conductive wrap and a third layer of S2 glass. the coil is then returned to the cavity and vacuum/pressure impregnated a second time. The details are described below:

The first step in the insulation process is to prepare the mold. It must be cleaned to remove any flash or residue from previous cycles. Spacer inserts are placed in the mold to compensate for the space filled by the second stage of the ground wrap discussed later. Mold release is applied to all mold surfaces expected to come in contact with the resin. One sheet of S2 glass is then placed in the cavity so that the trailing edges may be overlapped after insertion of all coil turns. This glass mat will become the inner portion of the ground shield. The process of cleaning and insulating the conductor itself is fairly simple. A self-driven mechanism is assembled on the conductor. It will follow the conductor but its weight will be supported by a mechanical arm stationed to a track on the floor inside the coil. The front part of the mechanism will contain the cleaning system which will consist of brushes followed by wipers. Sketches of the system are contained in section C-2. Dust will be evacuated and pulled away through a tube likewise attached to the mechanical arm. Following the cleaning system will be an eddy current sensor to

inspect the conductor surface and detect flaws. A three spool taping head which will wrap the polyimide film and the glass tape around the conductor is mounted just after the eddy current sensor. Sketches of the proposed taping system are shown in section C-2 but do not show the cleaning nor eddy current systems. Splices will be made in the insulation as required. Splices in the glass material will be scarfed and sewn together to maintain their mechanical strength. Kapton will be spliced by taping it together. As the conductor is insulated it will drop into the curing mold and be properly positioned with removable spacers which will be used to assure build dimensions are maintained as insulation proceeds.

Once all turns are fitted within the mold, the top will be placed on the mold and sealed. O-ring type seals will be placed over the leads and helium stub connections. All these connections must be air-tight. Once the chamber is considered air tight the vacuum plumbing and epoxy plumbing are attached. A trial evacuation is performed to assure vacuum integrity. Leaks will be detected by pressurizing the mold and soap testing or pressurizing with helium and sniffer testing depending upon the severity of the leak. After successful evacuation, strip heaters on the outside of the mold are connected to the power source and the mold is heated to 100°C to drive out the moisture entrapped within the S2 glass insulation. The vacuum system will be used to draw off the moisture liberated during the preheating. The coil will be cooled to pre-cure temperature (roughly 60°C) after it has been determined all the moisture is removed. The epoxy is added to the vat and heated to (roughly 60°C). The vat is sealed and evacuated while stirring the epoxy. Degassing is observed through the view port in the top of the chamber. Upon completion of degassing the chamber is flooded with nitrogen and opened. Catalyst is added and the vat closed. Stirring and degassing are repeated. After the vat, transfer lines, distribution plenum, and coil have all attained pre-cure temperature, epoxy is metered into the form. Back pressure on the vat is provided by dry nitrogen. Fill is monitored by watching the overflow sight glasses. When epoxy can be seen in all the sight glasses the form is considered fully impregnated. Individual sight glasses are valved off so they may be sealed as epoxy is observed in them. This ensures even filling of the mold. The form is then pressurized through the overflow ports with dry nitrogen to some pressure (100 PSI or below) to minimize the size of any remaining voids..

SCHEMATIC OF VPI SYSTEM

Coil Insulation and Impregnation

Pressure is reduced to just above atmospheric and the heat cycle is initiated. Strip heater temperature is monitored by thermocouples and controlled by an external controller as part of the VPI system control system. The cure cycle will not be discussed in detail since it is strictly a function of the epoxy vendors' recommendations. The control system will have sufficient flexibility to accept a number of different cure cycles with such things as cure times, hold temperatures, ramp rates, and number of cycle holds all being programmable from the keyboard.

Upon completion of the cure cycle the insulation blanket is removed and the coil is allowed to cool. Vacuum and epoxy plumbing connections are removed. Care

must be taken in breaking these fittings to assure cracks do not propagate into the coil. This risk will be minimized with proper design of the connections. The case must then be disassembled for coil removal. The strap clips are knocked out from below the coil to facilitate installation of lifting straps. The coil is lifted from the bottom of the form and transferred to the handwork stands for removal of epoxy

flash and dressing of the exterior surface of the coil. The coil is inspected and released for the second VPI process. A sketch of the coil at this point in the process is shown above for clarity in the relationship of the various components.

The balance of the insulation process involves application of the external ground layer. The second layer consists of a half-lapped layer of S2 glass followed by a wrap of conductive foil with a small overlap, followed by another layer of S2 glass. After the conductive foil is wrapped around the coil a conductive ground strap is attached to the foil for later grounding the coil. This material is applied by hand while the coil is sitting on supports. The supports are moved under the coil as necessary to provide access

for wrapping. The coil is replaced in the VPI mold with the spacers removed from the

mold. A second VPI cycle is performed which is basically identical to the first. The outer layer of vacuum impregnated S2 glass is intended to provide a protective barrier for the conductive layer. The coil is removed from the mold and cleaned up. The coil as it looks after the second VPI is shown below. The coil is inspected and tested. Dimensional data is recorded for later use in positioning the coil within the case.

System Description:

The VPI system for the TPX coils is not significantly different from similar systems needed for impregnation of motor/stator windings. The large size of the coils to be impregnated would require a very large vacuum chamber, if VPI were to be done in a chamber. We have chosen not to use an external chamber. The above layout describes the equipment plan and relationship between the system components. The main parts of the system are the vacuum system, pressurization system, epoxy flow system, and the impregnation mold.

Vacuum System:

The vacuum system will consist of a vacuum pump(s) capable of pulling down the mold volume to a vacuum level in excess of 10^{-4} torr in less than 15 minutes. Since neither the level of water retention in the insulation system nor the air evolution of the resin during mixing can be quantified, it is not meaningful to require vendors to quote on a vacuum system in terms of time needed to evacuate the coil or remove air from the resin. The vacuum system will be attached to the top of the resin vat as well as the mold to pull air from the resin during mixing. It will be tied to the overflow tubes on the mold as shown in the layout so that vacuum can be uniformly pulled on the entire mold. The only other significant requirement for the evacuation system is that the pumps must not backstream oil which would contaminate the resin.

Pressurization System:

Pressure must be applied to the resin in the coil after vacuum impregnation in order to drive the resin in further and minimize void size. In order to assure that no impurities are introduced to the system by the pressurization, dry bottled nitrogen will be used to meet the pressurization requirements. Nitrogen will be plumbed to the overflow lines in the mold. Pressure will be up to 100 PSI. Sufficient excess resin will be stored in the overflow columns to account for the volume reduction due to pressurization.

Epoxy System:

The epoxy system consists of the mixing tank and the plumbing system required to deliver the resin to the mold. The aspect ratio of the tank will insure a large surface area is provided for out-gassing of the resin. A tank of three feet in diameter and three feet deep will meet the needs of all the coils with the exception of PF6 and

PF7 which will require a larger mixing tank. The tank will be stainless steel with stainless steel motor driven mixers to simplify cleaning. The top of the tank will contain a light to

illuminate the interior of the tank and a viewing port to observe the out-gassing of the resin. The tank must be able to be evacuated to 10^{-4} torr without leakage. The tank will be heated by externally mounted heaters and thermostatically controlled to maintain the epoxy temperature to within 5°F of the set point within the tank. The tank is connected to the mold with a plumbing system to facilitate smooth flow of the resin into the mold. Resin is delivered to a central plenum in the center of the coil and distributed out the bottom of the mold by a series of smaller pipes. Piping outside of the mold will be traced with heat tape to insure the resin is not chilled during delivery to the mold. The inlet pipes are spaced approximately 2 feet apart around the bottom centerline of the mold. This spacing insures that the coil will not contain any dry spots or voids after impregnation. The distribution system is shown to the left.

Impregnation Mold:

The mold is the key to proper impregnation. It must hold the vacuum of 10^{-4} torr, hold the pressure of 100 PSI and be heated to 160°C without leakage. The mold must support and contain the coil during insulation, but must be completely disassembled after impregnation and curing to facilitate coil removal. The mold will consist of a base plate, side plates and top plates. All plates will be made from stainless steel, have o-ring seal grooves, and bolt together to form the mold. The bottom plate will be attached to a frame which will provide the structure of the mold. The side plates will have overlapping joints

in which o-rings will be placed to seal the mold. The side plates will have gussets to tie them to the bottom plate and provide side support. The mold will be fit together and leak tested before the coil is placed inside. This will allow any leaks to be repaired or filled. The top plates would then be removed and the coil insulated and placed inside. The assembled mold will again be leak tested after the coil is placed inside. Strip heaters will be mounted on the sides of the mold and they will be broken down into zones for control purposes.

Cartridge heaters will be installed in the top of the mold and controlled similar to the strip heaters. The entire mold will then be wrapped in a removable insulation blanket to hold the heat during curing.

C-2 INSULATION EQUIPMENT DRAWINGS

C-3 CLEANING, INSULATING AND VACUUM PRESSURE IMPREGNATION PRELIMINARY PROCEDURE

ACCELERATOR AND MAGNET SYSTEMS	TF COIL CLEANING, INSULATION AND VACUUM PRESSURE IMPREGNATION	OP-TPX-00003 8/1/95 Rev. 00
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SCOPE :

This specification establishes preliminary cleaning, insulation and vacuum pressure impregnation procedures and provides supporting information for the Torodial Field (TF) Coils of the Tokamak Physics Experiment (TPX).

GENERAL NOTES:

1. Plan List and Change Notices are to be checked to ensure that this is the most recent revision of the OP and any applicable Addendum.
2. For information regarding safety and proper use of any applicable chemicals, consult the Material Safety Data Sheet (MSDS). These sheets are available from the foreman.
3. All chemicals, when not in use, are to be stored in an approved storage container.
4. All waste (i.e. rags, chemicals, etc.) are to be disposed of properly, in accordance with company policies.
5. Safety equipment (i.e. gloves, safety glasses, coveralls, etc.) are to be worn when applicable.
6. Precautions are to be taken to maintain the cleanliness of the environment and individual parts.
7. If any unusual conditions are observed, immediately contact the supervisor.

SUPPORTING DOCUMENTS

DOCUMENT NAME	DOCUMENT NUMBER
Cleaning Procedure	TBD
VPI Procedure	TBD
TF Coil Case Assembly Procedure	TBD
Coil Verification Test Plan	TPX-Plan-VTP
Material Handling Procedure	TBD

PURPOSE:

The purpose of this document is to provide procedures for the cleaning, insulating and vacuum pressure impregnation of the reacted TF coil windings.

1. TRANSFERRING CONDUCTOR TO CLEANING/INSULATION STATION

- 1.1 Transport the coil to the insulation work station and remove the hold down plates.
- 1.2 Attach a second coil form base to the top of the coil restraints.
- 1.3 Install the turn support rods to the bottom of the coil.
- 1.4 Remove the bottom coil form base.

NOTE: SPACER PLATES OMITTED FOR CLARITY

FIGURE 1. COIL RESTRAINT

- 1.5 Lift the coil to the upper position for separating the turns.
- 1.6 Off-line, coat the parts of the VPI mold with a release agent.
- 1.7 Assemble the VPI mold and position below the coil.
- 1.8 Position the inner ground wall insulation of S2 fiberglass into the VPI mold. Fold the top edges of the insulation over the cavity walls.

2. CLEANING AND INSULATING PROCESS

- 2.1 With the coil in the support stand above the VPI mold, starting from the bottom layer of the coil (see Figure 3), reposition the hold up rods in the clamping station (see Figure 2) to allow each individual turn to be lowered. Clamping stations will be distributed 18" apart around the coil.

NOTE: SPACER PLATES OMITTED FOR CLARITY.

FIGURE 2. CLAMP HOLDING RODS

2.2 During the separation of a turn, remove the incoloy spacers between turns and layers. (see Figure 3).

FIGURE 3. LOWERING OF INSULATED CONDUCTOR INTO VPI MOLD

2.3 Position the eddy current head on the conductor, to confirm that there are no cracks.

2.4 Clean each individual turn with scotch brite and/or ethanol (depending on the condition of the material as received) to remove residue from the reaction process, whether this process will be done manually or mechanically is (TBD). Further instructions on cleaning procedure are (TBD).

2.5 Wrap conductor with a single or double application of a 1/2 lapped wrap of polyimide tape (.001"/.002") and a single 1/2 lapped wrap of s-glass tape (.014"). This process will be implemented with wrapping heads.

2.6 As each turn is insulated, place the insulated conductor down into the VPI mold. (see Figure 3). Positioning of the conductor into the VPI mold will be monitored by QC.

2.7 As the conductor is placed into the VPI mold, triangular s-glass corner roving shall be properly feed. Place the roving into voids formed by the corner radius of the conductor.

2.8 Repeat steps 2.2-2.7 for each turn and pancake.

2.9 Complete the inner ground wall insulation, by scarfing the insulation across the top of the coil.

2.10 Manually wrap insulation on helium stubs. The insulation will consist of (2) wraps of (.001") polyimide film lapped at 48% and (2) wraps of (.024") S2 glass also lapped at 48%. Use a tactifier to hold the insulation in place until the coil is vacuum pressure impregnated.

2.11 Electrical test megger shall be performed to confirm that there are no major faults.

2.12 Install the sealing fixture mechanism in the throat area.

3. VACUUM PRESSURE IMPREGNATION PROCESS

3.1 After the cleaning and insulating have been completed and the cover plate has been secured onto the VPI mold.

3.2 Connect the VPI mold to the epoxy and vacuum processing equipment. (see Figure 4)

3.3 Connect the epoxy manifold to the holes on the bottom of the VPI mold using flexible tubing.

3.4 Connect the epoxy supply line to the threaded hole on the manifold using a long 1" dia. plastic line.

3.5 Mount and distribute transparent, plastic, 4" dia. epoxy overflow columns on top of the VPI mold.

3.6 Close epoxy supply line valve.

3.7 Measure and pour the resin into the resin supplier and the hardener into the hardener supplier. Operator will use vacuum and PLC controls to flow components into the epoxy mixer.

3.8 Turn on the epoxy mixer vacuum, the epoxy mixer heater and the agitator motor to mix and degas the epoxy. During degassing, vacuum pressure shall reach 10^{-3} torr and temperature shall be maintained at the temperature recommended by the resin manufacturer. Near the completion of degassing vacuum pressure shall attain a level of 10^{-5} torr

SCHEMATIC OF VPI SYSTEM

FIGURE 4

3.9 During the mixing process, observe degassing bubbles through the observation ports. Continue mixing and vacuum at or above 10^{-3} for 40 minutes, then check for bubbles. If bubbles are still present continue mixing and vacuum.

3.10 Once the bubbles have cleared, turn the agitator motor off and continue the vacuum until just before the VPI is started.

NOTE: Steps 3.8-3.11 and 3.12-3.16 shall be performed concurrently.

3.11 Charge the VPI mold with dry air at 100°C to facilitate using convection to dry out the coil.

3.12 Heat the coil to 100°C . The temperature of the coil will be determined by the thermocouples attached to the surface of the VPI mold.

3.13 Shut off the heating elements and the convection fans.

3.14 Immediately turn on the VPI mold vacuum pump and start pumping out air and moisture vapors as the coil is cooling.

3.15 Pull vacuum until two conditions are met.

- A. The coil has cooled to the impregnation temperature recommended for the resin being used.
- B. The vacuum has reached 10^{-5} torr.

NOTE: In the event that the coil has cooled below the recommended temperature before reaching this vacuum level it must be reheated.

3.16 With the coil at 60° C and the epoxy degassed and heated to 60° C, gradually open the proportional valve in the epoxy supply line.

3.17 Flow the resin into the VPI mold from the bottom at a controlled rate. The rate will be slow enough so that the vacuum pump can maintain a vacuum of 10^{-1} torr.

3.18 Liquid level indicators will signal when the coil is totally immersed and there is enough resin to keep it submerged during the pressure part of the cycle. Excess epoxy will be stored in the epoxy overflow columns.

3.19 Observation ports will be provided to visually confirm full epoxy coverage and the absence of any bubbles in the resin above the coil.

3.20 The hold period (length TBD) of the vacuum cycle will start after (3.19) and (3.20) confirms no continuing activities and the vacuum level has reached 10^{-3} torr. The vacuum will be maintained at 10^{-3} torr or below during the entire holding period.

3.21 After the hold period, release the vacuum and apply pressure by filling the VPI mold with dry nitrogen at 100 psi. Hold pressure for one hour. Use the relief pressure valve to release the pressure.

3.22 With the VPI mold filled with dry nitrogen and the circulating fans turned on, turn VPI mold heaters on. The exact curing temperature will depend on the resin being used.

NOTE: The temperature gradient within the coil is critical. Heat application shall be controlled with a rate of change of coil temperature not to exceed 20° C /hr. Controllability of ramp rate shall be (+0 - 5° C) and the tolerance on the temperature setting shall be +/-3° C. The pressure relief valve shall be used to prevent any over pressures during the curing cycle, due to elevated temperature.

3.23 Once the curing temperature is reached, as indicated by a set of thermocouples on the surface of the coil, the coil shall dwell at a set temperature for a specific amount of time. The dwell time and temperature will be as recommended by the resin manufacturer.

3.24 Gradually decrease the temperature to (temperature TBD), the rate of decrease shall not be more than 20° C /hr.

3.25 After successfully completing the impregnation and curing procedure, disassemble the reusable bolted VPI mold and remove the coil. Transport the coil to the next work station where the electrostatic shield will be applied.

3.26 Note and repair any imperfections of the coil by rounding the corners, removing flashings and filling voids with fiberglass fibers. Thoroughly inspect the condition of the ground wall insulation.

3.27 Apply ground wall insulation, by manually wrapping the coil with (2) wraps of S2 fiberglass tape (.024" thick and 2" wide) with a 48% lap. This wrapping must be carefully applied around the base of the helium stubs.

3.28 Carefully wrap the helium stub (see Figure 5) to the specified contour. Extra layers of tape with a greater lap percentage will be required to obtain the necessary build.

4. Conductive Electrostatic Shield

4.1 Apply the conductive shield by manually wrapping the conductor with a 5% lapped wrap of 2" to 3" wide creped aluminum tape. This conductive tape is made up of an insulating film bonded to aluminum foil and then creped to 25 to 50% stretch (TBD).

4.2 To prevent a completed turn current path the starting end must be insulated by wrapping a short distance (1") with .005" polyimide film. Then the finishing end will lap only .5" of the starting end. Thus the electrostatic shielding is continuous without any contact between the starting and finishing end of the conductive tape. Locate this at the edge of the throat area.

4.3 Do not apply the 2" tape between the leads and helium stubs. Instead install a creped aluminum preform as shown in (Figure 6).

4.4 Use caution to assure that the conductive shield presents a good electrode toward the energized components along all edges of the cut out (see Figure 5).

4.5 Perform electrical testing.

4.6 Attach insulated lead to the electrostatic shield.

5. External Ground Plane Insulation

5.1 Apply the external ground plane insulation over the electrostatic shield, by manually wrapping the coil with a 1/2 lapped wrap of S2 fiberglass tape (.040" thick and 2" wide).

6. Second VPI

6.1 Reassemble the VPI mold around the coil and perform the second VPI. Follow steps 3.2 through 3.25.

6.2 After successfully completing the second VPI, disassemble the VPI mold and remove the coil.

6.3 Inspect the condition of the coil, note and repair any imperfections.

6.4 Perform electrical test.

7. Final Potting and Curing

7.1 Install the coil into the final case.

7.2 Insulate and seal around the leads and helium nozzles.

7.3 Reference the TF Coil Case Assembly Procedure for the final potting and curing of the insulated coil.

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE

Contract B235308

SDRL 23

FMECA

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PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**TORODIAL FIELD MAGNET ASSEMBLY
FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS
(FMECA)
SDRL 23**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

13-950811-BW-PConde-06

The original signed document is on file at the TPX Project Office.

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1.0 Introduction

This TPX TF Magnet System Failure Modes Effects and Criticality Analysis (FMECA) is prepared in accordance with TSOW §1.2.6 and SDRL 23. The FMECA process has been a significant communication vehicle between B&W's internal engineering, manufacturing, test and QA disciplines and General Atomics, our technical team member.

This FMECA is the primary tool of the TPX TF Magnet Assembly Reliability, Availability, and Maintainability (RAM) effort. It enables the team to determine, evaluate, and minimize risk areas in achieving RAM goals, as well as to focus the program's assets on where they will do the most good.

The FMECA is continuously being updated to support configuration trade-offs and testing decisions.

This preliminary FMECA is a working document representing a configuration in its development cycle. It is generated, in part, from a review of historical magnet failure databases, inputs from our design team, our manufacturing, and quality assurance staff and from the knowledge and experience of General Atomics, in running the DIII-D tokamak.

The FMECA process has identified some alternatives to consider for improving availability and the more general RAM program has already impacted design. The FMECA revisions will reflect the status of the design, from a RAM point of view, and propose preventive/mitigating actions, where appropriate.

To gain insight into tokamak operations, we are teamed with General Atomics to further reduce development risk by integrating our systems and design experience with the additional design and "lessons learned" expertise that they bring to the table. General Atomics is an active participant in the B&W TF Magnet Assembly FMECA process.

The B&W FMECA status and approach has been discussed with LLNL personnel on various occasions in the Technical Interchange Meetings. A working draft copy dated 5/95 was provided to LLNL, and no comments have been received. B&W has also contacted, via telecon, the Systems Integrator, TRW, to discuss RAM issues and requested comments on the FMECA draft.

2.0 Methodology

The FMECA is consistent with the guidelines of MIL-STD-1629A, and has been prepared concurrently with the system design effort so that the design may benefit from the associated analysis, conclusions, and recommendations. It identifies the cause and effect relationship between the failure modes of the different materials or components and the effects of these failure modes. The effects of these failure modes are assigned severity factors that are used in prioritizing areas that have an identifiable risk in achieving the availability goals.

The FMECA is generated as follows:

- a) The level of analysis and indenture of documentation is determined by engineering judgment on a case by case basis.
- b) The function of each part/assembly being analyzed is provided.
- c) Realistic mode(s) of failure for each component/subsystem analyzed are provided. Each failure mode identified has a separate identification number. The identification number is a unique reference designation followed by '\x', where x is an alpha character in alphabetic order representing additional failure modes. The reference designation numbers may be found in Appendix B.
- d) For each failure mode, the cause or causes are identified. The cause explains how a failure could occur.
- e) For each failure mode, an attempt to identify and suggest failure detection methods has been performed. The capability to detect and isolate a fault has a significant impact on availability.
- f) The likelihood of occurrence of each failure mode is assessed according to Table 1.
- h) Each failure mode has a severity assessment according to Table 2.
- i) For each "significant" failure mode cause mitigation and/or controls are identified. These may include design features, specific qualification tests, inspections, manufacturing process controls, etc. that help minimize the likelihood of the failure mode cause.
- j) For Phase II, the FMECA will include an assessment of Mean Time to Repair (MTTR) for each component/subsystem analyzed. It will be based on engineering judgment or our manufacturing/test experience. The assessment will be for operations performed on B&W hardware. It is intended for use by the System Integrator, in conjunction with the maintenance action information of the other systems, to arrive at the system level MTTR for a given fault. This will also assist in leading to an availability assessment versus the 0.97 allotted requirement(ref. A-Spec).

Table 1
TF Magnet Assembly Probability of Occurrence Categories

Level	Level Identifier	Definition
A	Frequent	A high probability of occurrence during the 10 year operating time interval.
B	Reasonably Probable	A moderate probability of occurrence during the 10 year operating time interval.
C	Occasional	An occasional probability of occurrence during the 10 year operating time interval.
D	Remote	An unlikely probability of occurrence during the 10 year operating time interval.
E	Extremely Unlikely	A failure whose probability of occurrence is essentially zero during the 10 year operating time interval.

Table 2
TF Magnet Assembly Severity Categories

Level	Level Identifier	Definition
I	Catastrophic	A failure that may cause the loss of the TPX, i.e. damaged beyond economic repair.
II	Critical	A failure that may cause major TPX or site damage that will result in TPX downtime of approximately one year or greater.
III	Marginal	A failure that may cause minor TPX or site damage that will/may result in system downtime of approximately a month or more and/or limit TPX functions.
IV	Minor	A failure that is not serious enough to cause TPX or site damage, but will result in system downtime (at convenience) or have a minor impact on TPX functions.
V	No Effect	A failure that has no impact on TPX operation and does not result in downtime.

Note: The TF Magnet System specification defines the required number of thermal and magnetic cycles expected during the 10 year period as follows:

- 300 cool-down / warm-up cycles
- 6,000 charge-discharge cycles
- 30,000 plasma pulses
- 5 million seconds total operating time
- 2 million seconds D operating time
- 50 quench cycles
- 15,000 plasma disruption cycles

Also note that when a failure mode probability is needed (for example, for failure mode criticality analysis) the highest failure mode cause probability is used to represent the failure mode probability unless otherwise specified.

The FMECA methodology, as described above, is consistent with that of MIL-STD-1629A. It considers failure mechanisms introduced during production and operation as well as life limiting events during operation.

The FMECA is an integral part of the TF Magnet Assembly development program. The analysis includes design issues, particularly where they may impact life. Where significant, these issues have been, and will continue to be, identified and added to the FMECA effort for the purposes of further assisting in the design and manufacturing development as it reflects on useful life and yield.

Figure 1 summarizes the role of the FMECA in the development process. Note that the FMECA is generated from several sources. It draws from the experience of other magnet programs (Magnet failure databases, GA's experience with DIII-D, FMECAs on other magnets), and initial analysis performed by the TPX team. As the FMECA developed, more emphasis was placed on inputs from engineering, production, and QA. These inputs were provided through dedicated FMECA meetings held at B&W for the purpose of identifying potential failure prone areas in the design and manufacturing of the TPX TF Magnet Assembly. Integrated Product Team (IPT) meetings also served as a source for information. Additionally, GA has also reviewed and provided feedback on prior versions of this report.

TPX TF Magnet Assembly FMECA Process
Figure 1

The FMECA has identified the TF Magnet Assembly most critical failure modes, listed in Table 3. This is a "watch list" that serves for special attention by program management and engineering. As previously noted, each failure mode in this FMECA was assigned a qualitative probability value from the probability of occurrence (PO) levels shown in Table 1. Each failure cause and effect was subjectively assigned a severity class (SC) from the scale shown in Table 2. Taken together, the PO and SC determine each component's criticality and serve to focus subsequent reliability engineering activity.

Table 3
TF Preliminary Critical Failure Modes

Item	Criticality	Failure Mode Descriptions
TFQD22A1\ a	II-C	Unable to meet or sustain the operating current.
TFQD24\ a	II-C	Winding pack insulation: short, current leakage.
TFQD22A2\ a	II-C	Conduit He leak- leading to arcing/short within coil.
TFQD22B\ a		He stub weld failure, leading to leak, short.
TFQD32A\ a		He lines/He isolator leak - leading to arcing/short
TFQD32C\ b		within TF Lead Box.
TFQB1\ a	II-C	Shorted He Isolator
TFQC1\ a		
TFQD31A\ a		
TFQD32C\ a		
TFQD\ a	II-C	Excessive field errors; misalignments.
TFQD2\ a		
TFQD42\ c		

Component criticality is the major factor used to determine which components make the Critical Item list. Figure 2 is a grid showing the 25 possible combinations of the PO and SC. For example, criticality II-D corresponds to components whose failure modes will occur with a remote likelihood, while resulting in a critical situation. The criticalities that appear "above" the gray area (labeled with "C") correspond to components that are critical items. Those criticality's "below" the gray area (labeled with "N") correspond to components that are not critical items. Due to the uncertainty in determining the PO and SC values, a band (main diagonal) of five criticalities correspond to components that are potentially critical items; these are labeled with "P" and appear in the gray area. Reliability engineering will continue to track failure modes in the "potential" category.

FIGURE 2
Probability of Occurrence/Severity Class (Criticality)
Criteria for Critical Items

		PROBABILITY OF OCCURRENCE				
		A	B	C	D	E
S E V E R E I T Y S	I	C	C	C	C	P
	II	C	C	C	P	N
	III	C	C	P	N	N
	IV	C	P	N	N	N
	V	P	N	N	N	N

WHERE:

- C indicates Critical Items
- P indicates Potential Critical Items
- N indicates Non-Critical Items

3.0 Format

The FMECA sheets of Appendix A are based upon traditional format of Mil-Std-1629 but have been expanded to include both preventive maintenance actions and maintenance times, important availability inputs.

The "Item No:" is the FMECA unique reference identifier and the failure mode letter following a "\". These identifiers may be found in Appendix B. The failure mode letters are lower case and listed sequentially. Thus if a particular assembly is associated with three modes, then 3 pages can be expected for that assembly lettered "\a", "\b", and "\c". Drawing numbers will be added to this field for cross reference in future submittals.

Note: Although intended to be sequential, the reference numbers used in this preliminary FMECA submittal reflect the nature of an evolving design effort. FMECA sheets have been added, deleted, combined, and resequenced based on design changes, ICD evolvment and resolution, changes in scope, and understanding of the TPX function. The final submittal will address the items presented in the TPX Physical Item Hierarchy controlled by B&W's Configuration Management, which represents all items necessary for delivery of a complete Magnet Assembly.

The "Subsystem Name:" provides the next higher assembly name. "Component Name" is the name of the item being analyzed. For example, page 42 of the FMECA in Appendix A, is for the Conduit, part of the Cable (CICC). Its reference number is TFQD22A2 (taken from the FMECA Reference Identifiers). The \b that follows indicates that this is the second failure mode discussed for that reference designation number.

The FMECA sheets contain the failure mode and causes that have been identified for an item to the lowest level of indenture found in the Reference Identifiers list. These sheets address all causes, from the component to the end item, associated with that particular failure mode. The PO and SC listed represents the evaluation of a single point failure worst case scenario. System or assembly FMECA sheets were created when the failure mode could not be adequately assigned to an individual component.

The initial seven FMECA sheets provide traceability from the system to the individual component FMECA sheets. The PO and SC listed reflects the highest level of criticality for that failure cause, from the list of component FMECA sheets (listed in Failure Prevention/Compensation column) which can ultimately cause that system level failure.

4.0 TF Magnet System Reliability Allocation

A preliminary reliability allocation has been performed one level below the Magnet System level. The allocated 0.9958 Magnet System shot reliability has been reallocated to the three subsystems as shown in Figure 3. These are preliminary allocations which should be reviewed once better information on the subsystems design is available.

Figure 3

**TF Magnet System
Preliminary Reliability Allocation**

5.0 Summary

The FMECA is an integral part of the B&W design process. Its generation is a team effort that includes design, systems, manufacturing, test, and QA engineering at both B&W as well as GA representation. This preliminary FMECA currently has identified 78 failure modes for reliability evaluation, and many times more potential causes. This tool is contributing to the design, manufacturing, and test programs as well as identifying critical QA inspections. In particular, it provides visibility to these team members of RAM risk areas permitting them to focus the program's assets on the most critical areas.

Engineering efforts has resulted in a design which incorporates many features to enhance the availability of the system. Replacing the CDR multiple coil lead configurations with single coil lead configuration is beneficial for manufacturing, and provides for a single configuration for spare procurement. The TF lead box has been chosen to be of a bolted type, with the components laid out to provide good access for repair actions. Tests have been recommended and incorporated into the test plans.

It is evident that there are many "potential critical items" in the FMECA. Better assessments of these failure mode sheets will be performed in Phase II when additional design and test information becomes available.

APPENDIX A

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

of the

Tokamak Physics eXperiment (TPX)

Toroidal Field Magnet Assembly

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. T1a Subsystem Name: Component Name: TF Magnet System		Function: A system which produces a toroidal magnetic field to confine the plasma, and instrumentation for monitoring superconducting state as well as other data gathering.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
TF Magnet Assembly nonconformance	1) Electrical failure.	Loss of TF Magnet System function, inhibiting research program.	Yes.	No		C	II	See TF\ a.
	2) Structural failure.					D	II	See TF\ b.
	3) Thermal system failure.					C	II	See TF\ c.
	4) Instrumentation failure.					C	III	See TF\ d.
	5) Excessive field errors.					C	II	See TF\ e.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TF\A Subsystem Name: TF Magnet System Component Name: TF Magnet Assembly		Function: A 16 coil assembly which produces a toroidal magnetic field to confine the plasma.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrical failure	1) Electrical conduction between octants.	Loss of TF Magnet System function, inhibiting research program.	Yes			C	III	See TFQA\A. See TFQD33D\B. See TFQD43B\B.
	2) Winding pack failure.					C	II	See TFQD22A1\A. See TFQD24\A. See TFQD33D\A.
	3) Splice joint failure.					D	II	See TFQB\A. See TFQB\B. See TFQC\A. See TFQC\B. See TFQD31\A. See TFQD31\B.
	4) He voltage isolator failure.					C	II	See TFQB1\A. See TFQC1\A. See TFQD31A\A. See TFQD32C\A.
	5) Grounding.					C	IV	See TFQD21\A. See TFQD41\A.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TF\b Subsystem Name: TF Magnet System Component Name: TF Magnet Assembly		Function: A 16 coil assembly which produces a toroidal magnetic field to confine the plasma. The PF and CS coils are supported at interfaces attached to the coil case assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	1) Coil case assembly failure.	Loss of TF Magnet System function, inhibiting research program.	Yes	No		D	II	See TFQD42\ a. See TFQD42B\ a. See TFQD42C\ a.
	2) Intercoil structure failure.					D	II	See TFQD\ b. See TFQD4\ b. See TFQD43\ a. See TFQD45E\ a.
	3) Winding pack failure.					D	II	See TFQD1\ a. See TFQ22A2\ b.
	4) Bolted joint assembly failure.					D	II	See TFQD43B\ a.
	5) Potting failure.					D	II	See TFQD1\ a.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TF/c Subsystem Name: TF Magnet System Component Name: TF Magnet Assembly		Function: A 16 coil assembly which produces a toroidal magnetic field to confine the plasma.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Thermal system failure.	1) Coil cooling failure	Loss of TF Magnet System function, inhibiting research program.	Yes	No		C	II	See TFQD2\b. See TFQD22A2\a. See TFQD22A2\c. See TFQD22B\a. See TFQD22B\b.
	2) Case cooling failure.					D	II	See TFQD42A\a.
	3) Splice cooling failure.					C	III	See TFQB\c. See TFQC\c. See TFQC\d. See TFQD31\c. See TFQD31\d. See TFQD31A\b.
	4) Intercoil structure cooling failure.					C	III	See TFQD43C\a.
	5) TF lead box component failure.					C	II	See TFQD32A\a. See TFQD33D\b.
	6) He isolator failure.					C	II	See TFQB1\b. See TFQC1\b. See TFQD32C\b.
	7) He filter failure.					D	III	See TFQD33C\a. See TFQD33C\b.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TF\d Subsystem Name: TF Magnet System Component Name: TF Magnet Assembly		Function: A 16 coil assembly which produces a toroidal magnetic field to confine the plasma.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Instrumentation nonconformance	1) Voltage tap failure.	Loss of TF Magnet System function, inhibiting research program.	Yes	No		C	III	See TFQB3\ a. See TFQC3\ a. See TFQD22A3\ a. See TFQD22A3\ b. See TFQD31C\ a.
	2) Fiber optics failure.					C	III	See TFQB3\ a. See TFQC3\ a. See TFQD22A4\ a. See TFQD31C\ a.
	3) Flowmeter failure.					C	IV	See TFQB2\ a. See TFQB2\ b. See TFQC2\ a. See TFQC2\ b. See TFQD33A\ a. See TFQD33A\ b. See TFQD31B\ a. See TFQD31B\ a.
	4) Strain gage failure.					B	IV	See TFQD46\ a. See TFQD46\ b. See TFQD46\ c.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TF/e Subsystem Name: TF Magnet System Component Name: TF Magnet Assembly		Function: A 16 coil assembly which produces a toroidal magnetic field to confine the plasma.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Excessive field errors	1) Misalignments between octants.	Loss of TF Magnet System function, inhibiting research program.	Yes	No		C	II	See TFQD\a.
	2) Misalignments between coil and case/coil cases within octant.					C	II	See TFQD42\c. See TFQD43\b.
	3) Improper coil shape.					C	II	See TFQD2\ a.
	4) Misalignments in FEC coil mounts.					D	III	See TFQD45C\ a.
	5) Misalignments in PF coil mounts.					D	III	See TFQD42C\ b.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQA/a Subsystem Name: Octant Assembly Component Name: E.C. Break (at Inner leg)		Function: Preclude toroidal Eddy current from flowing in the center post region.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrical insulation failure (continues ...)	1) Defects in insulating material. 2) Damage to insulation during quadrant assembly or handling. 3) Life limiting events on the material; loads due to installation, thermal/magnetic cycles, seismic events. 4) Damage during cyclic operation due to foreign objects/uncleanliness. 5) Arcing along the edges of materials (surface tracking) especially at fasteners. 6) Mechanically induced failure of the sheet insulation between wedged case walls. Stresses produced by misalignments. Abrasion.	1) Difficulty in plasma start up. 2) Additional heat loads from I^2R heating.	1) After quadrant assembly, test for 1kV voltage standoff. 2) After TF magnet system installation or upon a TPX maintenance action, test as part of system checkout procedure. 3) Operation, excessive quenching of a quadrant due to heat load.	None. Unless periodic replacement due to limited life determination.		C	III	1) Insulation to be qualified for cryogenic/radiation operation. Testing per the "Material and Component Test Plan", TPX-PLAN-MCTP. 2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c. 3) Manufacturing will ensure removal of all surface particulate per the Assembly Procedures. 4) Proper quadrant assembly and alignment procedures will be developed in Phase II.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQA/a (Cont) Subsystem Name: Octant Assembly Component Name: E.C. Break (at Inner leg)		Function: Preclude toroidal Eddy current from flowing in the center post region.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Electrical insulation failure)	7) Foreign object shorts across joint. 8) Insulation sheet shifts or slips out. 9) Frost build up. 10) Long term radiation degradation.							5) Redundant insulation sheets. 6) Engineering design to mechanically capture the insulation sheet.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQB/a Subsystem Name: TF Quadrant Assy Component Name: Intermodule Splice		Function: Provide electrical connection between two adjacent Quadrants.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
High electrical resistance	<p>1) Process error due to fracture of Nb₃Sn during handling (transportation/ installation); soldering operation (post reaction strain limitation exceeded); solder reflow during seal welding; cross contamination between welding & solder operation; during splice formation (conduit removal, Cr strip, Cu block/solder operations, coil leads alignment, bolting).</p> <p>2) Fatigue.</p> <p>3) Electrical overstress.</p> <p>4) Thermal cycling (CTE differences).</p> <p>5) Wrong solder material.</p> <p>6) Presence of contaminants at soldering.</p>	<p>1) Low current through coil cable; degradation of magnetic field. In the severe case, terminate TPX experimental run.</p> <p>2) Increased heat load on the refrigeration system.</p>	<p>1) Monitor change in resistivity via voltage tap.</p> <p>2) Degradation of magnetic field.</p> <p>3) Electrical Check at temperature.</p> <p>4) Excessive boil of cryogens, detected by flow meters.</p>	None		D	II	<p>1) Process development and room ambient test per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>2) Splice joint to be qualified for TPX operation (MIT tests?).</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQBb Subsystem Name: TF Quadrant Assy Component Name: Intermodule Splice		Function: Provide electrical connection between two adjacent Quadrants.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Splice block mechanical failure (causing open or high resistance)	<p>1) Bolts not properly tightened at installation or become loose during operation.</p> <p>2) Case unable to properly accommodate cyclic thermal/magnetic environment in the joint (maintain compression).</p>	<p>1) Low current through coil cable; degradation of magnetic field. In the severe case, high resistance of joint, terminate TPX experimental run.</p> <p>2) Damage to Nb₃Sn cable.</p>	<p>1) Change in resistivity via voltage taps</p> <p>2) Degradation of magnetic field.</p> <p>3) Excessive boil of cryogenics, detected by flow meters.</p>	Check bolts torque while performing scheduled or corrective maintenance for other assembly.		D	II	<p>1) Splice joint to be qualified for TPX operation (MIT tests?).</p> <p>2) Use of a locking device or material on bolts (differential fasteners?). Details to be worked out in Phase II.</p> <p>3) Current design incorporates support elements to the splice joint to react cyclic loads.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQB/c Subsystem Name: TF Quadrant Assy Component Name: Intermodule Splice		Function: Provide electrical connection between two adjacent Quadrants.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He leak	1) Failure of a CICC to joint case interconnect, improper weld, fatigue due to thermal, quenching, magnetic or seismic cycles. 2) Weld failure of any of the He supply/return lines or instrumentation. 3) Mechanical kink of supply tube. 4) Overpressure of conduit/piping.	1) Inadequate cooling of the joint can result in increased resistance, possible quench. 2) He leak of this joint will result in a degraded cryostat vacuum, an increased refrigeration load, eventual TPX downtime.	1) Degraded cryostat vacuum. 2) Change in resistivity via voltage tap 3) Flow meter may detect. 4) Degradation of magnetic field.	None		D	II	1) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b. 2) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 3) Splice joint to be qualified for TPX operation (MIT tests?). 4) TPX Project to monitor instrumentation data. 5) TPX project to consider vacuum pressure gauge.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQBI/a Subsystem Name: Intermodule Splice Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate splice joints from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrically shorted.	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p> <p>3) Flashover through gaseous He generated during a quench, and the high voltages (up to 15kV).</p> <p>4) Contamination: conductive particles, oils.</p> <p>5) Frost buildup on exterior body of insulator due to TPX Cryostat leak.</p>	A short to the He lines causing major damage to the insulator and surrounding components.	Loss of TF magnet system operation.	None.		C	II	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Isolator safety factor of 10 times required length under normal conditions.</p> <p>4) Isolators will be tested as part of an assembly kit per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>5) TPX project responsible for Cryostat integrity.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQBI\6 Subsystem Name: Intermodule Splice Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate splice joints from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He Leak	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p> <p>3) Weld failure.</p>	<p>1) Inadequate cooling, can result in excessive heating and increased quench frequency, by decreasing the conductor temperature margin. Inability to remove the operational heating sources.</p> <p>2) Degrade/destroy cryostat vacuum which results in increased refrigeration load, eventual TPX downtime.</p>	<p>1) Increased quenching.</p> <p>2) Flow meter/ pressure gauge may detect.</p> <p>3) Vacuum pressure gauge.</p>	None		C	III	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) Weld qualification and welder certification per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQB2/a Subsystem Name: Intermodule Splice Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Incorrect reading	1) Component failure. 2) Instrumentation out of calibration. 3) Pressure oscillations in plumbing. 4) Impurity material buildup in flow sensor leading to incorrect readings. 5) Erosion. Cause 4 & 5 due to particulate such as weld slag, grinding dust, corrosion.	1) Failure to detect quench by this quench detection circuit on splice joint; if normal zone undetected by other techniques, resultant damage to joint/leads. 2) False indication of quench will be ignored by system if other techniques do not sense quenching of the joint.	1) Transient or erratic reading. 2) Persistent incorrect reading. 3) TPX instrumentation software could detect problem by setting upper and lower bounds of correct operation.	1) Calibration. 2) Replace marginal units at earliest convenience.		C	IV	1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits. 2) Cleanliness control during assembly/storage. 3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) TPX project has responsibility for adequate purging of the system. 5) TPX project to monitor He quality from TF refrigeration system.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQB2\b Subsystem Name: Intermodule Splice Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Pressure sensing tubing blockage (if sensor of this type)	1) Foreign object (weld slag, grinding dust, corrosion) or He impurity.	Inaccurate or no flow reading. Loss of this quench detection circuit on the splice joint; if normal zone undetected by other techniques, resultant damage to the joint/leads..	Persistent incorrect reading.	None		C	IV	<p>1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits.</p> <p>2) Cleanliness control during assembly/storage.</p> <p>3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) TPX project has responsibility for adequate purging of the system.</p> <p>5) TPX project to monitor He quality from TF refrigeration system.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQB3a Subsystem Name: TF Quadrant Assy Component Name: Intermodule Splice		Function: Detect quench, through continuous interferometric measures or reflectometry or using a "balanced bridge" algorithm on adjacent double pancakes, as it begins to occur to prevent catastrophic damage to the joint.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Cable Instrumentation failure	<p>Open/shorted voltage tap/fiber optics due to:</p> <p>1) Damaged during splice formation, cut induced at termination.</p> <p>2) Damaged during operation; thermal cycling or Lorentz forces acting on cable, causes open.</p> <p>3) Operation; latent defect of the wire/fiber.</p>	<p>Loss of this quench detection circuit; if normal zone undetected by other techniques, resultant damage to magnet.</p>	<p>1) During assembly, test after conduit weld/coil winding/ and at TF Magnet assembly.</p> <p>2) Operation, detection through persistent misreading.</p>	None		D	III	<p>1) LLNL to qualify quench detection sensors for TPX life cycle environments.</p> <p>2) Splice joint forming procedures will be developed in Phase II.</p> <p>3) Quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits.</p> <p>4) Quench detector testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQCa Subsystem Name: TF Quadrant Assy Component Name: Module to BUS Joint		Function: Provide electrical interface between TF magnet assembly and power BUS.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
High electrical resistance	<p>1) Process error due to fracture of Nb₃Sn during handling (transportation/ installation); soldering operation (post reaction strain limitation exceeded); solder reflow (during seal welding; cross contamination between welding & solder operation); during splice formation (conduit removal, Cr strip, Cu block/solder operations, coil leads alignment, bolting).</p> <p>2) Fatigue.</p> <p>3) Electrical overstress.</p> <p>4) Thermal cycling (CTE differences).</p> <p>5) Wrong solder material.</p> <p>6) Presence of contaminants at soldering.</p>	<p>1) Low current through coil cable; degradation of magnetic field. In the severe case, terminate TPX experimental run.</p> <p>2) Increased heat load on the refrigeration system.</p>	<p>1) Monitor change in resistivity via voltage tap.</p> <p>2) Degradation of magnetic field.</p> <p>3) Electrical Check at temperature.</p> <p>4) Excessive boil of cryogens, detected by flow meters.</p>	None		D	II	<p>1) Process development and room ambient test per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>2) Splice joint to be qualified for TPX operation (MIT tests?).</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQC\b Subsystem Name: TF Quadrant Assy Component Name: Module to BUS Joint		Function: Provide electrical interface between TF magnet assembly and power BUS.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Splice block mechanical failure (causing open or high resistance)	<p>1) Bolts not properly tightened at installation or become loose during operation.</p> <p>2) Case unable to properly accommodate cyclic thermal/magnetic environment in the joint (maintain compression).</p>	<p>1) Low current through coil cable; degradation of magnetic field. In the severe case, high resistance of joint, terminate TPX experimental run.</p> <p>2) Damage to Nb₃Sn cable.</p>	<p>1) Change in resistivity via voltage taps</p> <p>2) Degradation of magnetic field.</p> <p>3) Excessive boil of cryogens, detected by flow meters.</p>	Check bolts torque while performing scheduled or corrective maintenance for other assembly.		D	II	<p>1) Splice joint to be qualified for TPX operation (MIT tests?).</p> <p>2) Use of a locking device or material on bolts (differential fasteners?). Details to be worked out in Phase II.</p> <p>3) Current design incorporates support elements to the splice joint to react cyclic loads.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQC/c Subsystem Name: TF Quadrant Assy Component Name: Module to BUS Joint		Function: Provide electrical interface between TF magnet assembly and power BUS.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He leak	<p>1) Failure of a CICC to joint case interconnect, improper weld, fatigue due to thermal, quenching, magnetic or seismic cycles.</p> <p>2) Weld failure of any of the He supply/return lines or instrumentation.</p> <p>3) Mechanical kink of supply tube.</p> <p>4) Overpressure of conduit/piping.</p>	<p>1) Inadequate cooling of the joint can result in increased resistance, possible quench.</p> <p>2) He leak of this joint will result in a degraded cryostat vacuum, an increased refrigeration load, eventual TPX downtime.</p>	<p>1) Degraded cryostat vacuum.</p> <p>2) Change in resistivity via voltage tap</p> <p>3) Flow meter may detect.</p> <p>4) Degradation of magnetic field.</p>	None		D	II	<p>1) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b.</p> <p>2) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>3) Splice joint to be qualified for TPX operation (MIT tests?).</p> <p>4) TPX Project to monitor instrumentation data.</p> <p>5) TPX project to consider vacuum pressure gauge.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQCd Subsystem Name: TF Quadrant Assy Component Name: Module to BUS Joint		Function: Provide electrical interface between TF magnet assembly and power BUS.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Inadequate He flow	1) Welding material or solder contaminants 2) Restricted He flow through the joint. 3) Coolant passages blocked by contaminants (i.e., frozen non-He gases). 4) Cooling passages blocked by mechanical distortion. 5) Unanticipated He flow regime or bubble blockage (vapor block due to high heat load).	Inadequate cooling of the joint can result in increased resistance, possible quench.	1) Voltage tap may detect the increased resistance. 2) Flow meter may detect.	None		D	II	1) Welder certification will be per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001, para. 3.3.1.2.b. 2) Design: use filters on the supply line to the joint (I don't see one). 3) He purity monitoring.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQC1a Subsystem Name: Module to BUS Joint Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate splice joints from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Electrically shorted.	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p> <p>3) Flashover through gaseous He generated during a quench, and the high voltages (up to 15kV).</p> <p>4) Contamination: conductive particles, oils.</p> <p>5) Frost buildup on exterior body of insulator due to TPX Cryostat leak.</p>	A short to the He lines causing major damage to the insulator and surrounding components.	Loss of TF magnet system operation.	None.		C	II	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Isolator safety factor of 10 times required length under normal conditions.</p> <p>4) Isolators will be tested as part of an assembly kit per the "Material and Component Test Plan", TPX-PLAN-MCTP.</p> <p>5) TPX project responsible for Cryostat integrity.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQC1\6 Subsystem Name: Module to BUS Joint Component Name: He Isolator		Function: Prevent TF Magnet Assembly electrical path through He pipes. Insulate splice joints from the He plumbing.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He Leak	<p>1) Cracks/defects on insulating material present at time of assembly, or appearing latter on, and aggravated by thermal cycling and vibration degradation.</p> <p>2) Differences in CTE of the materials.</p>	<p>1) Inadequate cooling, can result in excessive heating and increased quench frequency, by decreasing the conductor temperature margin. Inability to remove the operational heating sources.</p> <p>2) Degrade/destroy cryostat vacuum which results in increased refrigeration load, eventual TPX downtime.</p>	<p>1) Increased quenching.</p> <p>2) Flow meter/ pressure gauge may detect.</p> <p>3) Vacuum pressure gauge.</p>	None		C	III	<p>1) Isolator to be qualified for TPX operation (MIT?).</p> <p>2) QA/Receiving inspection will be performed per the QA Plan (SDRL 13), T5B-00001 Rev A, Criterion 7, which is in compliance with DOE Order 5700.6c.</p> <p>3) Perform leak test at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) Weld qualification and welder certification per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQC2a Subsystem Name: Intermodule Splice Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Incorrect reading	<p>1) Component failure.</p> <p>2) Instrumentation out of calibration.</p> <p>3) Pressure oscillations in plumbing.</p> <p>4) Impurity material buildup in flow sensor leading to incorrect readings.</p> <p>5) Erosion.</p> <p>Cause 4 & 5 due to particulate such as weld slag, grinding dust, corrosion.</p>	<p>1) Failure to detect quench by this quench detection circuit on the splice joint; if normal zone undetected by other techniques, resultant damage to the joint/leads.</p> <p>2) False indication of quench will be ignored by system if other techniques do not sense quenching of the joint.</p>	<p>1) Transient or erratic reading.</p> <p>2) Persistent incorrect reading.</p> <p>3) TPX instrumentation software could detect problem by setting upper and lower bounds of correct operation.</p>	<p>1) Calibration.</p> <p>2) Replace marginal units at earliest convenience.</p>		C	IV	<p>1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits.</p> <p>2) Cleanliness control during assembly/storage.</p> <p>3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p> <p>4) TPX project has responsibility for adequate purging of the system.</p> <p>5) TPX project to monitor He quality from TF refrigeration system.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQC2\b Subsystem Name: Intermodule Splice Component Name: Flow Sensor		Function: Detect quench as it begins to occur by monitoring the loss of flow, flow increase, and flow reversals associated with the appearance of a normal zone.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Pressure sensing tubing blockage (if sensor of this type)	1) Foreign object (weld slag, grinding dust, corrosion) or He impurity.	Inaccurate or no flow reading. Loss of this quench detection circuit on the splice joint; if normal zone undetected by other techniques, resultant damage to the joint/leads.	Persistent incorrect reading.	None		C	IV	1) Magnet quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits. 2) Cleanliness control during assembly/storage. 3) Flow meter testing at final acceptance will be performed per the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 4) TPX project has responsibility for adequate purging of the system. 5) TPX project to monitor He quality from TF refrigeration system.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQC3\A Subsystem Name: TF Quadrant Assy Component Name: Module to BUS Joint		Function: Detect quench, through continuous interferometric measures or reflectometry or using a "balanced bridge" algorithm on adjacent double pancakes, as it begins to occur to prevent catastrophic damage to the joint.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Cable Instrumentation failure	Open/shorted voltage tap/fiber optics due to: 1) Damaged during splice formation, cut induced at termination. 2) Damaged during operation; thermal cycling or Lorentz forces acting on cable, causes open. 3) Operation; latent defect of the wire/fiber.	Loss of this quench detection circuit; if normal zone undetected by other techniques, resultant damage to magnet.	1) During assembly, test after conduit weld/coil winding/ and at TF Magnet assembly. 2) Operation, detection through persistent misreading.	None		D	III	1) LLNL to qualify quench detection sensors for TPX life cycle environments. 2) Splice joint forming procedures will be developed in Phase II. 3) Quench detection is redundant, it requires quench sensing from 2 out of 3 detection circuits. 4) Quench detector testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD ^a Subsystem Name: TF Quadrant Assembly Component Name: TF Octant Assembly		Function: A 2 coil subassembly of the TF magnet assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Alignment failure	<p>1) Alignment failure during assembly, i.e., Wedging of TF noses, nose radius, coil to the case, coil to coil within the case structures, E.C. Break face positioning, bolted connection face positioning, TF to PF interface surface positioning, FEC interfaces surface positioning cold mass interface positioning, C.S. mounting face positioning.</p> <p>2) Alignment failure during operation, positional changes due to thermal movements.</p>	Failure to meet error field and ripple requirements will reduce the confinement capability of the tokamak unless correctable by field error correction coils.	None.			C	II	<p>Aggregate positional errors amongst the 16 coils must be less than 1mm:</p> <p>1) Coils will be positioned in cases utilizing octant fiducials as reference points for alignment per the "TF Case Assembly Procedure", OP TPX-00004. Multiple alignment checks of the coil against fiducials will be performed at various assembly steps.</p> <p>2) Manufacturing will machine the wedging faces to tight tolerances to ensure a proper fit.</p>
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD/a (Cont) Subsystem Name: TF Quadrant Assembly Component Name: TF Octant Assembly		Function: A 2 coil subassembly of the TF magnet assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Alignment failure)								<p>3) Bolted joint design will allow fit-up during assembly, or readjustment latter on. The G10 pieces will be machined to the proper dimensions for octant alignment.</p> <p>4) Proper procedures to correct misalignment problems will be developed in Phase II.</p> <p>5) Magnetic field measurement will be performed at installation per "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD b Subsystem Name: TF Quadrant Assembly Component Name: TF Octant Assy		Function: A 2 coil subassembly of the TF magnet assembly.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure- coil support.	CICC motion: 1) Lead movement. 2) Failure of the lead spurs to structurally anchor the leads, where the leads exit the coil. 3) Bad potting process.	1) Loss of coil. An improper mechanical support to the coil can result in damage to the coil by: exceeding superconductor strain limitation, structural deformation of CICC, cracking of insulation leading to short, He leaks. 2) Can result in failure to meet error field and ripple requirements which in turn will reduce the confinement capability of the tokamak unless correctable by error field coils.	1) Quench monitoring. 2) Loss of toroidal confinement capability. 2) Loss of coil capability.	N/A		D	II	1) QA controls of materials. 2) Final potting will be performed in accordance with the "TF Case Assembly Procedure", OP TPX-00004. (Tooling has windows to perform visual checks of the potting degassing. Higher vacuum levels will be used for degassing versus coil potting. Potting will be done in two steps, allowing inspection of the partially potted winding pack.) 3) The lead spur and the support members for the leads are being added to the design. Details will be available in Phase II.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD1a Subsystem Name: Octant Assy Component Name: Potting Compound		Function: Provide structural support for winding pack.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Structural failure	1) Fatigue. 2) Incorrect compound or curing (wrong E modulus). 3) Contamination of potting compound. 4) Voids due to inadequate outgassing.	Failure of the potting can lead to: a) electrical short of the coil due to insulation failure by the appearance of cracks. b) improper load transmission. c) potential motion of coil resulting in quench; cyclic fatigue leading to breakdown of insulation, resulting in short.	No	None		D	II	1) QA controls of materials. 2) Final potting will be performed in accordance with the "TF Case Assembly Procedure", OP TPX-00004. (Tooling incorporates windows to ensure visual checks of the potting degassing (absence of bubbles). Higher vacuum levels will be used for degassing versus coil potting. Potting will be done in two steps, allowing an intermediate inspection of the partially potted winding pack.)

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD2a Subsystem Name: TF Octant Component Name: Winding Pack Assy		Function: The winding pack contains the superconducting coil which generates a magnetic field (8.4T peak) when supplied with current (up to 33.5kA), the necessary insulation to prevent shorts amongst the CICC's and surrounding structures and also provides for structural support to maintain coil shape, the CICC's which also provide structural support as well as conduct He during operation, a grounding shield which prevents the coil from being presented with localized high electric fields during quench, and the quench detection cables.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Excessive field error.	Incorrect, or unable to maintain, "D" shape geometry due to: 1) Coil Springback. 2) Manufacturing tolerances and tooling. 3) Improper CICC bending and forming. 4) Structural variances along conduit length. 5) Aging of material in heat treatment, longitudinal shrinkage. 6) Distortions introduced during insulation application and reacting. 7) Weld failure, crack in conduit, fatigue.	Incorrect toroidal field profile will result in failure to meet error field and ripple requirements which in turn will reduce the confinement capability of the tokamak unless correctable by FEC coils.	1) Inspection. 2) NDT.	N/A		C	II	Aggregate positional errors amongst the 16 coils must be less than 1mm: 1) QA to ensure dimensional controls as called out in the "Coil Verification Test Plan", TPX-PLAN-VTP, Appendix B. 2) Crack detection after the reaction procedure will be performed per the "Material & Component Test Plan", TPX-PLAN-MCTP, and "Coil Verification Test Plan", TPX-PLAN-VTP.
(continues ...)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD2a (Cont) Subsystem Name: TF Octant Assembly Component Name: Winding Pack Assy		Function: The winding pack contains the superconducting coil which generates a magnetic field (8.4T peak) when supplied with current (up to 33.5kA), the necessary insulation to prevent shorts amongst the CICC's and surrounding structures and also provides for structural support to maintain coil shape, the CICC's which also provide structural support as well as conduct He during operation, a grounding shield which prevents the coil from being presented with localized high electric fields during quench, and the quench detection cables.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Excessive field error)								3) The "TPX Coil Winding Equipment Specification", TPX-SPEC-133-0002, details the many features and tolerances the winding machine is required to meet.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET

Item No. TFQD2\b Subsystem Name: TF Octant Assembly Component Name: Winding Pack Assy		Function: The winding pack contains the superconducting coil which generates a magnetic field (8.4T peak) when supplied with current (up to 33.5kA), the necessary insulation to prevent shorts amongst the CICC's and surrounding structures and also provides for structural support to maintain coil shape, the CICC's which also provide structural support as well as conduct He during operation, a grounding shield which prevents the coil from being presented with localized high electric fields during quench, and the quench detection cables.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTRR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Uneven coolant flow in parallel cooling paths. (continues ...)	1) Production tolerances. 2) Blockages from contamination. Particulate such as: weld slag, grinding dust, rust, corrosion. 3) Pressure leaks and resulting cooling differences. 4) Void fraction differential between paths in adjacent double pancakes. Allowable void fraction is $36 \pm 4\%$. 5) Localized damage or deformation of strands due to He stub installation process. 6) High heat load causing vapor lock.	Operation with localized marginal or inadequate cooling leading to quench.	1) Flow meters may detect condition.	None.		D	III	1) 4) Flow impedance testing during assembly and at final acceptance will be performed per the "Coil Verification Test Plan", TPX-PLAN-VTP, and "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. 2) Cable supplier to ensure dimensional controls on the inner surface of the CICC, cable strands conduit, quench protection system cabling. 3) TPX Project QA to develop cleanliness requirements. (End caps on CICC for transportation and storage?)

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD2b (Cont) Subsystem Name: TF Octant Assembly Component Name: Winding Pack Assy		Function: The winding pack contains the superconducting coil which generates a magnetic field (8.4T peak) when supplied with current (up to 33.5kA), the necessary insulation to prevent shorts amongst the CICC's and surrounding structures and also provides for structural support to maintain coil shape, the CICC's which also provide structural support as well as conduct He during operation, a grounding shield which prevents the coil from being presented with localized high electric fields during quench, and the quench detection cables.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Uneven coolant flow in parallel cooling paths.)								4) B&W Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. 5) Westinghouse to develop and qualify He stub installation.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD21a Subsystem Name: Winding Pack Assembly Component Name: Groundplane Shielding		Function: A conductive surface to provide plasma noise shielding to the superconducting coils. The shielding also ensures that during a quench the coil is not presented with a nonuniform field due to variations present in the surface conditions of the coil case.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Open	1) Cold solder joint (strap). 2) Damage during assembly. 3) CTE of materials.	Reduced noise shielding to the coil.		Inspect/test at convenience while access to the interior of TF Lead Box. (The grounding strap attachment point is in the TF Lead Box opening, for ease of inspection and repair.)		D	IV	1) Manufacturing will apply and test the shield per the "TF Coil Cleaning, Insulation, and Vacuum Pressure Impregnation", OP-TPX-00003. The shield acts as added noise shielding to the coil (the case also provides some shielding). The significance of tears/holes in the shield is dependent of the wavelength of the noise signal. Phase II work.

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A1a Subsystem Name: Cable (CICC) Component Name: Superconductor		Function: Superconductor cable made out of 486 composite Nb ₃ Sn /Cu stands, capable of carrying 33.5 kA at a peak field of 8.4T and at an operating temperature between 5 to 6.5 K, in order to produce a magnetic plasma confining toroidal field when configured in the TPX specified geometries.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
Unable to meet or sustain the operating current. (continues ..)	1) Damage elements prior to shipment to B&W: a) raw materials do not conform. b) strand diameter nonconformance, neckdown. c) kinks, breaks, crossovers, cuts. d) plating: gaps, thickness, incomplete, non adhering. e) contamination: corrosives, chips, inclusions. f) improper thermal processing. g) damage during conduit welding. h) contamination due to foreign particles through the ends or on the surface of the conduit. i) overstrain/work harden.	1) Unable to reach or maintain the required toroidal field strength. 2) Coil ramp rate limitation. 3) Quench before operating current is achieved.	1) At start up: Inability to attain operating current, quench. 2) During operation: Quench detection system will detect localized heating, inability to confine the plasma, quench.	None.		C	II	1) Handling procedures for all stages of assembly after reaction of the coil and for the joint connections will be developed in Phase II. 2) A lead supporting /protection structure (to prevent damage during handling or transportation) has been specified in the operating procedures. A lead support is added in the design to react operational loads. 3) Reaction process will be characterized to establish acceptable repeatability. 4) Cable supplier must meet tight specifications. B&W QA will review all

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A1/a (Cont) Subsystem Name: Cable (CICC) Component Name: Superconductor		Function: Superconductor cable made out of 486 composite Nb ₃ Sn /Cu stands, capable of carrying 33.5 kA at a peak field of 8.4T and at an operating temperature between 5 to 6.5 K, in order to produce a magnetic plasma confining toroidal field when configured in the TPX specified geometries.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Unable to meet or sustain the operating current).	<p>2) Variability stackup in the cable/conduit dimensions along the CICC geometries. (These may be a factor at the spooling/winding operations, causing strand abrasions, stretching or neckdown).</p> <p>3) Strands damaged during the winding process.</p> <p>4) Damage to the conductor strands during helium feed-through installation; boring through the Incoloy wall and welding the He stubs in place. This includes foreign particle introduction (i.e., metallic particles from the boring process) and heat damage to conductor.</p>							<p>documentation to ensure all relevant processes were in control at the time of delivery of the CICC to B&W.</p> <p>5) B&W facility to explore provisions to compensate for a utility power interruption during the reaction process. Equipment will incorporate limited self power features per "TPX Coil Reaction Equipment Specification", TPX-SPEC-133-0003</p> <p>6) Cryogenic test at octant assembly level is recommended, and is incorporated into the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. Many</p>
(continues ..)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A1/a (Cont) Subsystem Name: Cable (CICC) Component Name: Superconductor		Function: Superconductor cable made out of 486 composite Nb ₃ Sn /Cu stands, capable of carrying 33.5 kA at a peak field of 8.4T and at an operating temperature between 5 to 6.5 K, in order to produce a magnetic plasma confining toroidal field when configured in the TPX specified geometries.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Unable to meet or sustain the operating current).	<p>5) Inadequate/improper Nb, Sn reaction temperature profile: i) error in specified profile, ii) equipment failure (heaters, controllers, sensors), iii) incorrect oven, tooling or charge instrumentation design</p> <p>6) Sintering of strands (i.e., may occur due to localized Cr strand coating damage or nonconformances).</p> <p>7) Excessive strain (>0.3%) after reaction cycle due to; the application of insulation, coil handling, octant level assembly, transportation, electrical joints connections.</p>							<p>opportunities for undetected damage to the superconductor exist, beginning at the cable supplier, through TPX assembly. Although sample tested, the condition of the coil's current carrying capability and ramp rate limitations won't be known until cold tested. Program risks, in terms of schedule and costs, of producing spares after one year are significant. Replacement coils would be more economically produced at the end of the production run, while the mechanisms for material procurement, tooling, and people are in place.</p>
(continues ..)								

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET
Failure Modes, Effects, and Criticality Analysis

Item No. TFQD22A1/a (Cont) Subsystem Name: Cable (CICC) Component Name: Superconductor		Function: Superconductor cable made out of 486 composite Nb ₃ Sn /Cu stands, capable of carrying 33.5 kA at a peak field of 8.4T and at an operating temperature between 5 to 6.5 K, in order to produce a magnetic plasma confining toroidal field when configured in the TPX specified geometries.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
(continued: Unable to meet or sustain the operating current).	<p>8) The cable in the CICC-joint area may be susceptible to operational cyclic loading, fatigue.</p> <p>9) Overstress from thermal cycling and/or thermal gradients during processing or operation. Nb₃Sn strain: increased strain in cooldown, Cu & brass go to yield, Nb₃Sn in compression.</p> <p>10) Increased strain due to Lorentz forces in longitudinal and transverse directions.</p>							<p>Significant modeling of the magnetic forces and fixture design for the single octant prototype testing will be performed in Phase II, production could benefit from this effort, for cold testing production units.</p> <p>7) Design must ensure that the CICC-joint interface does not transfer mechanical stresses to the cable and can withstand the thermal cycling without fatigue. The module to buss joint will experience significant displacement as the TF structure cools down.</p>

TOKAMAK PHYSICS EXPERIMENT, TF MAGNET

Item No. TFQD22A2/a Subsystem Name: Cable (CICC) Component Name: Conduit		Function: Incoloy 908 structure which provides a sealed conduit for He coolant flow and structural support of the superconducting cable.						
Failure Mode	Failure Causes and Mechanisms	Failure Effects	Failure Detection	Preventative Maintenance	MTTR (Hrs.)	PO	SC	Failure Prevention/ Compensation
He leak	1) Bad virgin tube (i.e. cracks, porosity). Base material wrong/ heat treats. 2) Conduit weld failure (seam or butt weld). 3) He stub weld failure. 4) CICC to Joint weld failure (at the leads end). (Weld failure causes: assembly error, contaminated weld area, embrittlement, or fatigue due to thermal, quenching, magnetic, plasma disruption or seismic cycles). 5) Undetected cracks originating from: i) Conduit forming process.	1) Increased load on refrigeration system. 2) Failure to cool portions of coil adequately leading to quench. 3) Cryostat vacuum degradation/destruction. 4) Generate helium pressure (near the Paschen curve minimum) within the confines of the potted coil, which can lead to a short given insulation weaknesses.	1) Quench monitoring. 2) Coolant flowmeter or pressure sensor may detect condition. 3) Increased refrigeration loads. 4) During assembly: NDT, Eddy current testing. 5) Vacuum monitoring, pressure gauge.	None.		C	II	1) LLNL will perform multiple inspection and tests operations of the CICC materials and processing prior to delivery to B&W. 2) Weld qualification and welder certification will be performed per the "TPX TF Magnet System Requirements Document", TPX-SPEC-013-0001. Weld testing (under worse case conditions) per the "Material and Component Test Plan", TPX-PLAN-MCTP. 3) Process cleanliness and furnace tooling design per the "TF Coil Reaction Procedure", OP TPX-00002, and "TPX Coil
(continues ..)								

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT AND MANUFACTURE

Contract B235308

SDRL 25

Long Lead Materials and Equipment

August 7, 1995

13-950807-BW-RRyan-01

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

SDRL 25

Long Lead Materials and Equipment

SDRL 25 is to be used to identify the long lead procurements required to support the TF TPX fabrication effort. Statement of Work: The subcontractor shall identify the long lead materials and equipment (exclusive of the sheathed superconductor) for the TF magnet system and prepare specifications and drawings as required in sufficient detail to allow the procurement action to be started. These documents will be reviewed and approved at the PDR.

The statement of work does not define "long lead". For the purposes of this work B&W has identified "long lead" as six months. For the purposes of this document material and equipment for which the span from order placement to receipt is longer than six months shall be referred to as "long lead". This span eliminates the need to track special steels and fiber composites which have spans on the order of 4 months. Given this definition and the exclusion of GFM superconductor the long lead items as identified on our integrated schedule are the Coil Winding Machine, Reaction Furnace, Vacuum Impregnation System and the TF coil case. Attached is the schedule for procurement of the first production coil case and the prototype coil case. Schedules for procurement of the three major pieces of equipment are contained in SDRL 22 as are descriptions of the equipment and procurement risk mitigation plans. Significant milestones for procurement of the major equipment are listed below:

TPX Coil Winding Equipment

Schedule of Deliverables

<i>Item</i>	<i>Description</i>	<i>Delivery</i>
0001A	Coil Winding Equipment	13 mos ARO
0001B	Design Review	3 mos ARO
0001C	As-built drawings	14 mos ARO
0001D	Operation and Maintenance Manuals, per Spec §3.4.2	13 mos ARO
0001E	Software, per Spec §3.4.3	14 mos ARO
0002	Installation and Training Services	13 mos ARO
0003	Spare Parts and Special Tools	14 mos ARO
0004	Maintenance and Repair Services	T&M, as reqd

TPX Coil Reaction Equipment

Schedule of Deliverables

<i>Item</i>	<i>Description</i>	<i>Delivery</i>
0001A	Coil Reaction Equipment	14 mos ARO
0001B	Thermal Analysis	4 mos ARO
0001C	Design Review	4 mos ARO
0001D	As-built drawings	16 mos ARO
0001E	Operation and Maintenance Manuals	14 mos ARO
0001F	Software	16 mos ARO
0002	Installation and Training Services	14 mos ARO
0003	Spare Parts and Special Tools	16 mos ARO
0004	Maintenance and Repair Services	T&M, as reqd
0005	Auxiliary Generator (option)	14 mos ARO

TPX Coil VPI Equipment

Schedule of Deliverables

<i>Item</i>	<i>Description</i>	<i>Delivery</i>
0001A	Coil VPI Equipment	6 mos ARO
0001B	Design Review	2 mos ARO
0001C	As-built drawings	8 mos ARO
0001D	Operation and Maintenance Manuals	6 mos ARO
0001E	Software	8 mos ARO
0002	Installation and Training Services	6 mos ARO
0003	Spare Parts and Special Tools	8 mos ARO
0004	Maintenance and Repair Services	T&M, as reqd

The schedules for the long lead items are tied to GFM deliveries and to each other. The first conductor delivery is 450 meters of TF dummy conductor (4/1/97). Upon receipt of

this material acceptance testing of the winding machine may begin so this date coincides with completion of the installation of the winding machine. The procurement schedule for the winding machine is thus stretched backward from the conductor delivery date with the activities required to procure the machine. The first conductor delivery and winding machine procurement thus form the critical path for the program. The reaction furnace is not needed until the dummy coil has been made. At that time we plan to acceptance test the reaction furnace using the dummy coil which should be representative of the production TF coil in terms of thermal mass. The VPI system will be acceptance tested using the dummy coil as well so the VPI system will be needed roughly one month after the reaction furnace acceptance test is initiated. Delivery of the first coil case is tied to completion of the first production coil, based on the assumption that the case for the prototype coil to be used in the cold testing at LLNL will have a special case of a simpler design than the production cases.

MAGNET CASE - PROTOTYPE

ID	Task Name	Span	Start	Finish	95	1996				1997				
					Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	Magnet Case	531d	9/20/95	10/1/97	Magnet Case									
					9/20	10/1								
2	Prepare Specifications	260d	9/20/95	9/17/96	Prepare Specifications									
3	Complete Drawings	90d	9/18/96	1/21/97	Complete Drawings									
4	Procurement	5d	1/22/97	1/28/97	Procurement									
5	Issue P.O. to Mt. Vernon	5d	1/22/97	1/28/97	Issue P.O. to Mt. Vernon									
6	Vendor Manufacture	146d	1/29/97	8/20/97	Vendor Manufacture									
7	Forging Process	100d	1/29/97	6/17/97	Forging Process									
8	1/4 Scale Weld Mock-up	61d	1/29/97	4/23/97	1/4 Scale Weld Mock-up									
9	Parts Machining	40d	4/24/97	6/18/97	Parts Machining									
10	Welding	20d	6/19/97	7/16/97	Welding									
11	Final Cavity Machining	20d	7/17/97	8/13/97	Final Cavity Machining									
12	Shipment	5d	8/14/97	8/20/97	Shipment									
13	Acceptance	30d	8/21/97	10/1/97	Acceptance									
14	Inspection	20d	8/21/97	9/17/97	Inspection									
15	B & W Acceptance	10d	9/18/97	10/1/97	B & W Acceptance									
16	Complete TF Proto Fabrication	0d	10/1/97	10/1/97	Complete TF Proto Fabrication									

Magnet Case									
Prepare Specifications									
Complete Drawings									
Procurement									
Issue P.O. to Mt. Vernon									
Forging Process									
1/4 Scale Weld Mock-up									
Parts Machining									
Welding									
Final Cavity Machining									
Shipment									
Acceptance									
Inspection									
B & W Acceptance									

MAGNET CASE - PRODUCTION

ID	Task Name	Span	Start	Finish	1996				1997				1998				1	
					Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
1	Magnet Case	530d	6/3/96	6/12/98	<div style="text-align: center;"> Magnet Case </div>													
2	Prepare Specifications	260d	6/3/96	5/30/97	<div style="text-align: center;"> Prepare Specifications </div>													
3	Complete Drawings	90d	6/2/97	10/3/97	<div style="text-align: center;"> Complete Drawings </div>													
4	Procurement	5d	10/6/97	10/10/97	<div style="text-align: center;"> Procurement </div>													
5	Issue P.O. to Mt. Vernon	5d	10/6/97	10/10/97	<div style="text-align: center;"> Issue P.O. to Mt. Vernon </div>													
6	Vendor Manufacture	145d	10/13/97	5/1/98	<div style="text-align: center;"> </div>													
7	Forging Process	100d	10/13/97	2/27/98	<div style="text-align: center;"> Forging Process </div>													
8	Parts Machining	40d	1/5/98	2/27/98	<div style="text-align: center;"> Parts Machining </div>													
9	Welding	20d	3/2/98	3/27/98	<div style="text-align: center;"> Welding </div>													
10	Final Cavity Machining	20d	3/30/98	4/24/98	<div style="text-align: center;"> Final Cavity Machining </div>													
11	Shipment	5d	4/27/98	5/1/98	<div style="text-align: center;"> Shipment </div>													
12	Acceptance	30d	5/4/98	6/12/98	<div style="text-align: center;"> Acceptance </div>													
13	Inspection/Installation	20d	5/4/98	5/29/98	<div style="text-align: center;"> Inspection/Installation </div>													
14	B & W Acceptance	10d	6/1/98	6/12/98	<div style="text-align: center;"> B & W Acceptance </div>													
15	First TF Production Conductor	0d	3/2/98	3/2/98	<div style="text-align: center;"> First TF Production Conductor </div>													
16	Complete First Quadrant of Coils	132d	4/29/98	10/29/98	<div style="text-align: center;"> Complete First Quadrant of Coils </div>													
17	Assemble/Deliver First TF Quadrant	130d	10/30/98	4/29/99	<div style="text-align: center;"> Assemble/Deliver First TF Quadrant </div>													

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