TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE

Contract B235308

SDRL 46

CPDR Review Package

August 18, 1995

13-950811-BW-C Weber-11

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

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

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

CONTRACTOR PRELIMINARY DESIGN REVIEW (CPDR)

- Welcome to the TF Magnet System
Contractor Preliminary Design Review
- Introduction
 - Logistics
 - Agenda
 - TF Project Accomplishments Summary
 - Organization
 - CPDR Scope
 - Conclusion

MASTER

ARRANGEMENTS AND LOGISTICS

- Escorts required for non-cleared personnel
- Telephone available in Room - #
- Library with all data and reports available in Room- #; do not remove
- Private meeting/caucus room available - Room -#
- Restrooms in rear around corner
- Use TPX/LLNL comment sheets for findings - refer to talk/slide #
- Schedule maintenance important - write finding, go off-line
- Break snacks/soft drinks available; no scheduled breaks
- Lunches provided
- Secretarial services available, messages will be forwarded
- CPDR chairman is Wayne Reierson; B&W chairman is C. Weber
- DRB to review and catalog findings; prepare/deliver PDR summary
- B&W to record meeting minutes and address findings

TF MAGNET CPDR AGENDA

MONDAY, SEPTEMBER 18

- 8:00** **LLNL CPDR Organization Briefing**
- 8:30** **CPDR Introduction, Agenda**
- 8:45** **TF System Design Description**
- 10:00** **Specifications and Verification Matrix**
- 10:30** **Interface Definition**
- 10:45** **Drawing Tree and Design Control**
- 11:00** **Electromagnetic Analysis**
- 11:45** **Lunch**
- 12:30** **TF Structure Design**
- 13:50** **Winding Pack Design**
- 14:50** **Magnet Interconnections**
- 15:20** **Thermal Design and Analysis**
- 16:20** **Instrumentation and Control**

TF MAGNET CPDR AGENDA
TUESDAY, SEPTEMBER 19

08:00	Coil Winding Process
09:00	Coil Reaction Process
09:45	Coil Insulation Process
10:30	Magnet Assembly
11:10	Preliminary Manufacturing Plan
11:50	Lunch
12:30	Reliability, Availability, and Support
13:00	Materials and Process Selection
13:15	Material and Component Testing
13:45	Coil Verification Tests
14:15	Magnet Acceptance Tests
14:35	Integrated TF Magnet Plan
15:00	DRB Caucus, Findings Development
16:45	DRB Report
17:00	Adjourn

TPX PROJECT SUBCONTRACT OBJECTIVES

- Phase I
 - Perform preliminary design and analysis and develop preliminary manufacturing methods and tooling for successful Preliminary Design Review
 - Perform manufacturing R&D in conductor bending/forming and reaction thermal processing to demonstrate feasibility
- Phase II
 - Develop final product, tooling and equipment designs for TF and PF Magnet systems verified by Final Design Review
 - Procure long lead equipment and material, final manufacturing methods development, prototype fabrication and testing
 - Fabricate, assemble, test, ship and installation assistance of 16 TF magnet coils and assembly structures and 14 PF magnet coils and assemblies

PROJECT STATUS SUMMARY AND MAJOR ACCOMPLISHMENTS

- Submitted all contract data items (SDRLs) on schedule
- Performed work using CSCSC compliant with DOE N4700.5
- Performed preliminary design and manufacturing activities on-schedule and on-budget (current CPR: SV= CV=)
- Developed TF Magnet and Configuration Items Specifications
- Developed preliminary Interface Control Documents
- Actively used FMECA in design process
- Advanced conceptual design to preliminary design; major features:
 - simplified structure, removed members lowered cost
 - developed bolted joint design
 - integrated design and manufacturing to provide needed alignment based on magnet field error requirements

PROJECT STATUS SUMMARY AND MAJOR ACCOMPLISHMENTS (cont'd)

- designed 8 identical octants and 16 identical
- applied material in high stress nose region, used forging
- developed case and intercoil cooling
- developed 3D baseline insulation; solved stress problem - patent pending
- case fabrication with Inconel 625 to reduce distortion, improve quality
- case cooling design developed
- preliminary design drawings also available electronically
- global structural model with integrated lower tier models
- new winding pack design with roll formed transitions
- lead insulation provides open lead box
- bolted joint design mitigates eddy current break movement for wedged configuration

PROJECT STATUS SUMMARY AND MAJOR ACCOMPLISHMENTS (cont'd)

- Demonstrated feasibility of fabrication for major processes
 - lead bending and roll forming initial characterization
 - reaction effects determined
 - demonstrated forming of various required configurations
 - produced various models
 - verified reaction model, system meets required reaction time-temperature profile
- Developed preliminary tooling and equipment designs

TOROIDAL FIELD MAGNET SYSTEM PRELIMINARY DESIGN AND MANUFACTURING R&D

- Work performed by Babcock & Wilcox - Accelerator & Magnet Systems, Lynchburg, VA.
 - Under subcontract B235308 to Lawrence Livermore National Laboratory
 - Supporting the Tokamak Physics Experiment at Princeton Plasma Physics Laboratory
- General Atomics supports B&W under subcontract

B&W Corporate Structure

B&W TPX Project Structure

Integrated Product Team

TF MAGNET PRELIMINARY DESIGN SCHEDULE

CPDR REQUIREMENTS

- TF Magnet Technical Statement of Work
 - Drawings
 - Supporting Analyses
 - Materials Selection
 - R&D Results
 - Preliminary FMECA
 - Preliminary System Design Description
 - Identify Long Lead Materials & Equipment
 - Preliminary Manufacturing Plan
- Entry/Exit Criteria
- Guidance of MIL-STD-1521B

MIL-STD-1521B PDR GUIDANCE

- Evaluate the progress, technical adequacy, and risk resolution (technical, cost and schedule) of the selected design approach
- Determine the design compatibility with performance specification
- Evaluated the degree of definition and assess the risk associated with selected manufacturing methods and processes
- Determine the existence and compatibility of the physical and functional interfaces among the configuration items

CPDR SCOPE CONFORMS TO TSOW

	TSOW Section
• Introduction	
– Objective and Agenda	1.1.1, 1.3.16.2
– System Design Description	1.1.1
• Specifications & Design Control	
– Specifications	1.2.1, 1.2.4
– Interface definition	1.2.2
– Drawing tree & design control	IV,V.5, 1.1.1
• Design & Supporting Analysis	
– Electromagnetic analysis	1.3.2
– Winding pack design	1.3.3, 1.3.20
– Structure design	1.3.4
– Thermal design	1.3.5
– Instrumentation	1.3.6
– Magnet interconnections	1.3.17

CPDR SCOPE CONFORMS TO TSOW

(Cont'd)

TSOW Section

- **Manufacturing**
 - Coil winding 1.3.7, 1.3.15.2
 - Coil reaction & cleaning 1.3.8, 1.3.15.1
 - Coil insulation 1.3.9
 - Magnet assembly 1.3.10
 - Manufacturing plan & Long Lead 1.2.8, 1.2.9, 1.3.19
- **FMECA, Test and QA Plans**
 - Reliability, Availability & Support 1.2.6
 - Materials & processes selection 1.2.5
 - Material & component testing 1.3.12
 - Coil verification testing 1.3.11
 - Acceptance testing 1.3.18
- **Phase II Plan**
 - Integrated magnet plan 1.3.14

CPDR SUPPORTING DATA

- Synopsis provided; gives summary, TSOW ref., supporting documents
- CPDR SDRL submittals:
 - #15 System Design Description
 - #17 TF Magnet System Specification
 - #18 Interface Control Documents (10)
 - #20 CI Specifications (4)
 - #21 Material & Process Selection
 - #23 FMECA
 - #22 Critical Equip. Drawings, Specifications, and Procurement Plans (D)
 - #25 Long Lead Material & Equipment
 - #29 Analysis Results
 - #30 Engineering Drawings
 - #31 Magnet Sensors
 - #32 Coil Assembly Documentation
 - #33 Coil Verification Test Plan
 - #34 Material & Component Test Plan
 - #36 Integrated Magnet Plan (TF Sch.)
 - #37 Manufacturing R&D Results (A-Reaction, B-Bendng)
 - #45 Acceptance Test Plan
 - #46 CPDR Package

CONCLUSION

- Preliminary design described
- All TSOW elements completed
- Verified preliminary TF design against requirements
 - analysis shows design meets requirements
 - manufacturing feasibility established
 - acceptable project risk
- TF magnet preliminary design review judged - Acceptable - by Design Review Board
- Authorize work for Phase II - establish final design, build and test prototype, production of TF magnet system

TF SDD Presentation

T. Antaya

75 min

- 1) Summ. Requirements - - - 5 min
- 2) Design Drivers and Design Constraints - 5 min
- 3) TF System Prelim. Design - - - 20 min
 - Summ. Conductor
 - Structure Design & Fab
 - Magnet Assembly
- 4) Analysis Highlights . - - - 10 min
 - Design, FMECA
- 5) R&D Highlights - - - 10 min
 - TF HDWR Pedigree (what comes from where)
 - Bend & Forming
 - HT

6) Final Design

20 min

Introduce:

- 25 min

Final Design Bolted TF structure

Disconnects w/ other WBS Elements
to correct

Magnet Fabrication Summary

70 min

- 75 min

Figure F-1 TF Magnet Configuration

F-3 Performance and Operational Requirements

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

F-4 RAM Requirements

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

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

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

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

Provisions for recovery shall be made for every failure mode which

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

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

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

1. TF SYSTEM DESIGN

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

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

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

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

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

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

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

CDR PARTS HEIRARCHY:

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

HAS BEEN SIMPLIFIED TO:

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

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

1.1 TF Conductor (WBS 132)

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

Figure 1.1-1 TF Conductor Cross Section

1.1.1 Strand

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

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

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

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

1.1.2 Cabling

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

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

Figure 1.1-2 Sensor Lead Positions

1.1.3 Conduit

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

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

Figure 1.2-1 TF Magnet Operating Space (Dwg. 1331002)

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

ITEM	PART NO	DESCRIPTION	QTY
1	133-5200	TF COIL WINDING ASSEMBLY	1
2	133-5200	POLYIMIDE INSULATION	TBD
3	133-5202	30 S2 GLASS TRIANGULAR WOVEN PREFORM	TBD
4	133-5201	0.014 30 S2 GLASS WOVEN TAPE	TBD
5	133-5204	0.024 30 S2 GLASS WOVEN TAPE	TBD
6	133-5205	ALUMINUM CREEP	TBD
7	133-5203	WINDING EPOXY	TBD
8	133-5220	TF WINDING SPACER 1	1
9	133-5221	TF WINDING SPACER 2	1
10	133-5222	TF WINDING SPACER 3	1
11	133-5223	TF WINDING SPACER 4	1
12	133-5224	TF WINDING SPACER 5	1
13	133-5225	TF WINDING SPACER 6	1

DETAIL Z
SCALE: 2.0

Figure 1.2-3 TF Winding (Dwg. D-1335100)

THE WINDING PACK PATH IS DEFINED AS THE
CICC CENTERLINE.

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

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

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

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

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

1.2.1.2 Coil Leads

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

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

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

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

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

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

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

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

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

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

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

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

Figure 1.2-5. Lead Box Top View

Figure 1.2-6. Lead Box Front View

Figure 1.2-8 Lead Support Structure

Figure 1.2-9 Typical Lead Hanger Assembly

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

COIL INSULATION

§ VIEWS

Figure 1.2-11 TF Octant Assembly

TF SDD Presentation 75 min ... T. Antaya

- 1) Summ. Requirements
- 2) Design Drivers and Design constraints
- 3) TF system Design
 - Summ. conductor
 - Coil Design
 - structure Design & FAB
 - Magnet Assembly and Alignment

} Present Status
- 4) Analysis Highlights Supporting Design
~~4) Analysis Highlights Supporting Design~~
- 5) R&D Highlights and Design Impact
 - Design Pedigree chart
 - [Q: BW only

SUB - ASSEMBLY FABRICATION

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

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

Figure 1.2-18 TF Octant Assembly Nomenclature

Figure 1.2-19 TF Octant Fabrication Sequence - Inboard Leg

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

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

Figure 1.2-22 Inter-Coil Structure Detail

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

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

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

Figure 1.2-26 Inboard Side Plate Weld Detail

Figure 1.2-27 Outboard Leg Weld Detail

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

Figure 1.2-29 Lead Box Structure

A hand-drawn oval shape with a long, curved tail extending from the top right side.

MAGNET ASSEMBLY

Figure 1.2-30 TF Magnet Bolted Joint

Figure 1.2-31 Bolted Joint Assembly Detail

Figure 1.2-32 Bolted Joint Insulation Detail

Figure 1.2-32 Bolted Joint Wedge detail

ANALYSIS HIGHLIGHTS

EFM Field Error Monte Carlo

Structural worst loads
Coil slip / case Interaction
Bolting Friction

Winding pack shear stress mitigation
(5x5 results avail?)

Thermal sm, lg quench
~~case~~ cooling

FMECA TOP 5

R&D Highlights

Pedigree :

Quench system MIT

Splice LLNL

~~Coil~~ Coil Forming BW

sheath cleaning BW

Insulation R&D WEC

Stub WEC

2.3.5 Coil Insulation R&D

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

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

2.3.6 Helium Stub Welding R&D

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

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

Figure 2.3.6-1 WEC Helium Stub Design

2.3.7 Coil Interconnection Component R&D

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

Figure 2.3.7-1 LLNL Splice Design

WHAT TO DO . . .

FINAL BOLTED Design . . .

PF }
Cryo }
reconcile |

Phase II

PLANS

Figure 3.3.2-2 Coil Winding Equipment Diagram

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

Figure 3.3.2-4 TF Coil Reaction Equipment

Figure 3.3.2-6 Conductor Wrapping Process

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

Figure 3.3.2-7 Coil Insulation at VPI Stages

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

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

Figure 3.3.2-8 VPI Equipment

Figure 3.3.2-10 Coil Installation in Inter-coil Structure

Figure 3.3.2-11 Case Cover Installation

Figure 3.3.2-12 Inter-Coil Splice Joint

Figure 3.3.2-13 Lead Box Installation

Figure 3.3.3-3 TF Magnet Factory Assembly and Acceptance

Figure 3.3.3-5 TF Magnet System Assembly and Verification

TF Magnet Specifications

**Bob Batchelder
B&W Systems Engineering**

Specification Topics

- **Specification tree**
 - Flowdown from Project documents
 - TF Magnet subsystems and components
 - Programmatic requirements
 - PDR entrance and exit criteria
- **System Specification (SDRL 17)**
 - "A" Spec comments
 - Remaining issues
- **Critical Item Specifications (SDRL 20)**
 - TF Coil Specification status and issues
 - Equipment CI Specification status and issues
- **Verification Requirements**

Requirements Flow-down

TF Subsystems and Components

* B&W responsibility
LLNL responsibility

Programmatic Requirements

PDR Entrance & Exit Criteria

- **TF Magnet System Specification**
 - Circulated for review with PDR package
 - Forms technical baseline for Phase II work
 - Objective: Project approval after PDR
- **Critical Item Specifications (B&W items)**
 - Circulated for review with PDR package
 - Mfg equipment is critical to Phase II schedule
 - Objective: LLNL approval after PDR
- **Subsystem & Component definition (LLNL items)**
 - Needed for Phase II design and process development

TF Magnet SRD (SDRL 17)

- **Informal spec discussions (outlines) 10/11/94**
- **Draft spec circulated 11/18/94**
- **Preliminary Specification Review 1/10/95**
 - Review committee finds TF Spec “acceptable”
 - Definition of LLNL items must be “timely”
- **“A” Spec draft release 5/9/95**
 - Establishes derivation and allocation of tokamak requirements
 - Closes many issues remaining from Prelim Spec Review
 - B&W comments returned 6/12/95
- **Revised drafts circulated 6/19/95, 7/12/95**
- **Current draft dated 8/15/95**

Administrative Issues

- **Approval list**
 - *Necessary LLNL and PPPL individuals*
- **Precedence of applicable documents**
 - *Currently in order of flow-down (charts 3 & 4)*
- **Document format**
 - *Currently MIL-STD-490A Type B1 (Prime Item)*
 - *Document number per TPX Controlled Document Standard*
- **Non-standard references**
 - *B&W NEE-1 for shipping loads*
 - *B&W M41-100 for support equipment*

Open Technical Items

<i>TF Spec ¶</i>	<i>Page</i>	<i>Requirement</i>
3.1.2.7	13	Tolerance on field strength (ref. SRD §3.2.1.4.1.2)
3.2.1.1	16	Plasma current definition (incorporate Bulmer memo in A Spec)
	16	Heat loads (incorporate Liew/Pillsbury memos in A Spec)
3.2.1.2	17	Define limit on 1,1 TF error
3.2.1.8	19	Define total time of magnet energization
3.2.3	20	Define failure rate for inaccessible components, eg. TF coils (10^{-6}?)
Various		Establish sources of requirements in A Spec or elsewhere

Magnet Requirements Verification

		<i>Analysis</i>	<i>Demo</i>	<i>Inspect</i>	<i>Test</i>
3.1.2	Interfaces		x	x	S
3.2.1	Performance				
3.2.1.1	Operating States	x			S
3.2.1.2	Magnetic Field	x			S
3.2.1.3	Quench Stability	x			P,S
3.2.1.4	High Voltage Breakdown	x			A,P,S
3.2.1.5	Elec. Isolation & Grndng	x	x		A,P,S
3.2.1.6	Instr. & Quench Detection		x		A,P,S
3.2.1.7	Cool-down & Warm-up	x			S
3.2.1.8	Op. Cycles & Useful Life	x			
3.2.2	Physical Characteristics		x		
3.2.3	Reliability and Availability	x			
3.2.4	Maintainability		x		
3.2.5	Environmental Conditions	x			
3.2.6	Transportability	x	x		
3.3	Design and Construction		x	x	

Test Codes: A = Factory Acceptance, P = Prototype, S = System

CI Specifications (SDRL 20)

- **TF Magnet Coil**
 - Establishes criteria for room-temperature coil verification
- **Winding Equipment**
 - Capability to wind TF + PF coils
 - Turn-to-turn accuracy objective ± 0.005 in.
- **Reaction Equipment**
 - Sized to react multiple TF and PF coils
 - Temperature variation from program $\pm 5^{\circ}\text{C}$
 - Redundant vacuum pumps, heaters; power backup
- **VPI Equipment**
 - VPI in mold (no autoclave)
 - Common system for TF + PF coils

Coil Requirements Verification

		Analysis	Demo	Inspect	Test
3.2.1	Performance				
3.2.1.1	Electrical Characteristics				A
3.2.1.2	Pressure and Leak Rate				A
3.2.1.3	Hydraulic Characterstics				A
3.2.1.4	Instrumentation				A
3.2.2	Physical Characteristics				
3.2.2.1	Coil DIensions			X	
3.2.2.2	Cooling Flow Path			X	
3.2.2.3	Grounding			X	
3.2.2.4	Critical Flaw Size			X	
3.2.2.5	Strain Limit after Reaction			X	
3.2.3	Reliability	X			
3.2.4	Maintainability		X		
3.2.5	Environmental Conditions	X			
3.2.6	Transportability		X		
3.3	Design and Construction		X	X	

Test Code: A = Factory Acceptance

TF Interface Definition

TF Interface Definition

- 10 interfacing subsystems identified
- Contacts established
- Program ICD format incorporated
- Interface concepts and and issues identified
- Preliminary ICDs released at July TIM
- *Many* details to be worked in next phase

TF to Vacuum Vessel (WBS 12)

- July 1995 status:
 - Preliminary envelopes coordinated
 - No contact between structures under any condition
 - Temporary assembly interface (defined in Assembly & Installation ICD)
- Next phase:
 - Continuing development of envelopes
 - Specification of heat loads
 - Nuclear radiation definition

TF to PF (WBS 14)

- July 1995 status:
 - PF-6 and PF-7 mount details, displacements and loads TBD
 - Preliminary verification matrix developed
 - CS attachment details TBD
- Next phase:
 - Review of new CS, PF-6 and PF-7 support design concepts
 - Definition of all support point loads and displacements

TF to Cryostat (WBS 15)

- July 1995 status:
 - Preliminary definition of vacuum interfaces
 - Cryostat pressure
 - Helium leak rates (individual joints)
 - TF outgassing rate design goal
- Next phase:
 - Envelope drawing development
 - Heat load definition/allocation

TF to Tokamak Support Structure (WBS 16)

- July 1995 status:
 - Interface responsibility separation identified
 - Clarification of TF support concept
- Next phase:
 - Review of modified TSS design concept
 - Definition of thermal loads and displacements
 - Definition of leakage currents

TF to Assembly & Installation (WBS 17)

- July 1995 status:
 - Concept for VV installation added
 - Incorporated TF bolted joint configuration
 - Responsibilities defined
- Next phase:
 - Fixture and attachment drawing development
 - Definition of VV temporary support details
 - Cable routing diagram development
 - Assembly and alignment procedure development

TF to FEC Coils (WBS 19)

- July 1995 status:
 - Established FECC mount accommodation of TF displacement
 - Maximum heat load clarified
 - Responsibilities defined
- Next phase:
 - Drawing development for FECC locations, mount details, lead supports
 - Definition of supported weights and electromagnetic loads

TF to Vacuum Pumping (WBS 34)

- July 1995 status:
 - ICD drafted as placeholder
- Next phase:
 - Coordination of envelope drawings
 - Definition of responsibilities
 - Development of interface details

TF to Power System (WBS 42)

- July 1995 status:
 - Defined slow dump discharge voltage
 - Identified need for tolerance on TF current, TF inductance and resistance
- Next phase:
 - Specification of TF current tolerances
 - Definition of TF Local I&C signal formats
 - Determination of room temp bus connection details

TF to Central I&C (WBS 61)

- July 1995 status:
 - Preliminary list of TF sensors and functions identified
- Next phase:
 - Review of Central I&C generic ICD when completed
 - Specification of data format details

TF to Cryogenic Equipment (WBS 72)

- **July 1995 status:**
 - Defined manifold sizes
 - Defined flow rates and pressures
 - Specified inlet and outlet relief valve pressures
 - Added preliminary heat load tables and fluid schematics
- **Next phase:**
 - Final cryo circuit schematic development
 - Definition of cryo line routing details
 - Definition of cryo connections to TF bus
 - Specification of cooldown profile, quench effects, flow imbalance details

Secondary TF ICDs

- July 1995 status:
 - Draft documents being developed by LLNL
 - TF to TF Local I&C (WBS 133/135)
 - TF to TF Bus & Leads (WBS 133/136)
- Next phase:
 - Support to document development

Drawing Tree & Design Control

R. Kunz

Overview

- Drawing List (CPDR/Vanguard)
- Physical Item Hierarchy
- Electronic Design Paradigm
- Future Interface Impact
- Design Software
- Design Validation
- End Item Marking
- Conclusion

Drawing List

- XX on Vanguard
- YY included in CPDR
- See spreadsheet

Drawing List, con't

- Excel Insert

TPX Preliminary Design Drawing List

Babco Wilcox
Lynchburg, Virginia

LIST #	PREFIX	NUMBER	SHEET	DWG. TITLE	ORIG.
1	E-	1334000	SH 1 OF 1	TOROIDAL FIELD OCTANT ASS'Y	GM
2	C-	1331000	SH 1 OF 1	TPX ABSOLUTE COORDINATE SYSTEM	AL
3	D-	1331002	SH 1 OF 1	TPX OPERATING SPACE	AL
4	D-	1332100	SH 1 OF 1	MAGNET SYSTEMS ENVELOPES	GM
5	D-	1334100	SH 1 OF 1	LEFT BOLTING ASSEMBLY	KG
6	E-	1334200	SH 1 OF 1	MACHINED INTERCOIL STRUCTURE ASS'Y	KG
7	E-	1334201	SH 1 OF 2	INTERCOIL STRUCTURE WELDMENT -SH. 1	KG
8	E-	1334201	SH 2 OF 2	INTERCOIL STRUCTURE WELDMENT -SH. 2	KG
9	D-	1334300	SH 1 OF 1	INBOARD LEG ASS'Y	KG
10	D-	1334700	SH 1 OF 1	LEAD BOX CLOSURE DETAIL	TT
11	D-	1335000	SH 1 OF 1	TF WINDING PACK	DS
12	D-	1335500	SH 1 OF 1	TF COIL WINDING ASS'Y	DS
13	B-	1336000	SH 1 OF 1	LEADBOX DETAIL	DS
14	E-	1336400	SH 1 OF 1	LEAD BOX SUPPORT STRUCTURE ASS'Y	DS
15	E-	1332000	SH 1 OF 1	TOROIDAL FIELD MAGNET STRUCTURE PENETRATIONS	GM
16	E-	1332101	SH 1 OF 1	TF to CS SYSTEM INTERFACE LOCATIONS	GM
17	D-	1332102	SH 1 OF 1	PF5U MOUNTING STRUCTURE	GM
18	C-	1332103	SH 1 OF 1	PF6U MOUNTING STRUCTURE	GM
19	C-	1333001	SH 1 OF 1	THERMAL MODEL CROSS-SECTIONS	AL
20	D-	1333101	SH 1 OF 1	TF HEMISPHERE CHARGING CIRCUIT	GM
21	D-	1333102	SH 1 OF 1	TF MAGNET OCTANT HYDRAULIC CIRCUIT	GM
22	B-	1333600	SH 1 OF 1	WINDING PACK TRANSITION REGION ENVELOPE	DS
23	E-	1334220	SH 1 OF 1	INTERCOIL STRUCTURE SUB-ASS'Y	KG
24	D-	1334221	SH 1 OF 1	INTERCOIL STRUCTURE SUB-ASS'Y	KG
25	D-	1334310	SH 1 OF 1	INBOARD LEG ICS ASS'Y	KG
26	D-	1334311	SH 1 OF 1	INBOARD LEG ICS ASS'Y	KG
27	C-	1334703	SH 1 OF 1	LEFT ACCESS PANEL	TT
28	C-	1334704	SH 1 OF 1	RIGHT ACCESS PANEL	TT
29	C-	1334801	SH 1 OF 1	ALIGNMENT WEDGE	KG

TPX Preliminary Design Drawing List

Babc Wilcox
Lynchburg, Virginia

LIST #	PREFIX	NUMBER	SHEET	DWG. TITLE	ORIG.
30	B-	1334802	SH 1 OF 1	STUD	KG
31	B-	1334803	SH 1 OF 1	WASHER	KG
32	B-	1334804	SH 1 OF 1	INSULATION SLEEVE	KG
33	C-	1334805	SH 1 OF 1	SUPERBOLT ASSEMBLY	KG
34	B-	1334808	SH 1 OF 1	WEDGE INSULATION	KG
35	C-	1334809	SH 1 OF 1	INBOARD LEG LOWER EC INSULATION PIECE	KG
36	C-	1334810	SH 1 OF 1	INBOARD LEG UPPER EC INSULATION PIECE	KG
37	D-	1335100	SH 1 OF 1	TF CICC WINDING	DS
38	C-	1335101	SH 1 OF 1	TF CICC PANCAKE WINDING PATH	DS
39	B-	1335102	SH 1 OF 1	TF CICC	DS
40	B-	1335501	SH 1 OF 1	HE STUB ASS'Y "A"	DS
41	B-	1335502	SH 1 OF 1	HE STUB ASS'Y "B"	DS
42	B-	1335503	SH 1 OF 1	HE STUB ASS'Y "C"	DS
43	B-	1335504	SH 1 OF 1	HE STUB ASS'Y "D"	DS
44	B-	1335505	SH 1 OF 1	HE STUB ASS'Y "E"	DS
45	B-	1336050	SH 1 OF 1	FLOWMETER	DS
46	B-	1336051	SH 1 OF 1	FILTER	DS
47	B-	1336052	SH 1 OF 1	HE ISOLATOR	DS
48	B-	1336100	SH 1 OF 1	INLET HEADER ASS'Y	DS
49	C-	1336110	SH 1 OF 1	FILTER/FLOWMETER/ISOLATOR ASS'Y	DS
50	C-	1336120	SH 1 OF 1	CASE WALL SUPPLY "A" LEFT ASS'Y	DS
51	C-	1336122	SH 1 OF 1	CASE WALL SUPPLY "B" LEFT ASS'Y	DS
52	C-	1336123	SH 1 OF 1	CASE WALL SUPPLY "B" RIGHT ASS'Y	DS
53	C-	1336130	SH 1 OF 1	ICS SUPPLY INTERNAL LEFT ASS'Y	DS
54	C-	1336131	SH 1 OF 1	ICS SUPPLY INTERNAL RIGHT ASS'Y	DS
55	C-	1336300	SH 1 OF 1	CASE COOLING RETURN ASS'Y	DS
56	C-	1336310	SH 1 OF 1	ICS RETURN ASS'Y-LEFT	DS
57	C-	1336311	SH 1 OF 1	ICS RETURN ASS'Y-RIGHT	DS

TPX Preliminary sign Drawing List

Babcr Vilcox
Lynchburg, virginia

LIST #	PREFIX	NUMBER	SHEET	DWG. TITLE	ORIG.
58	D-	1336401	SH 1 OF 1	HANGER BRACKET FRAME ASS'Y	DS*
59	D-	1336456	SH 1 OF 1	SPUR ASS'Y	DS*
60	C-	1336501	SH 1 OF 1	LEFT LOWER BUSHING	TT
61	C-	1336502	SH 1 OF 1	LEFT UPPER BUSHING	TT
62	C-	1336503	SH 1 OF 1	RIGHT LOWER BUSHING	TT
63	C-	1336504	SH 1 OF 1	RIGHT UPPER BUSHING	TT
64	B-	1336700	SH 1 OF 1	HE INLET TUBE	DS

Physical Item Hierarchy

- B&W design innovations have reduced PIH from CDR
- Interchangeability and Manufacturing similarity now achieved across TF system
- Allows greater flexibility for meeting field error requirements, if needed.

Physical Item Hierarchy

CDR PARTS HEIRARCHY:

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

HAS BEEN SIMPLIFIED TO:

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

Physical Item Hierarchy

- Insert

Electronic Design Paradigm

ELECTRONIC DESIGN PARADIGM

Compliant, Manufacturable, Inspectable

Future ICD Impact

- Impact from late interface changes
 - TF/PF
 - WEC proposed changes after 7/7 (act 7/1) closeout
 - Impact to interfaces location on CS structure
 - Cases added to PF-6 & -7 - impact to loading
 - Needs negotiation after CPDR

Future ICD Impact, con't

- TF/TCM
 - Bolted instead of welded interface - impact is need for bolt recesses, drill and tap
 - Some structural load support change - needs Phase 1a negotiation

Future ICD Impact, con't

- TF Cryogenics
 - At July TIM, LLNL showed case cooling after bus return
 - Need to resolve lead routing with LLNL after CPDR

Design Software

- IDEAS (IGES)
- ANSYS
- TOSCA
- QUENCHER - FORTRAN
- TEMPEST - FORTRAN

Design Validation

- All design analysis and drawings reviewed by TF Magnet Design Chief
- Compared to prior Project results
- Cross model comparison
- Ongoing TIM input/comments
- IPT Process

End Item Marking

- All end item marking requirements included on drawings
 - varies by part
 - all drawings (incl. marking req'ts) will be validated/approved by Project prior to Procurement of delivered hardware

Conclusions

- Necessary drawings included in CPDR package and on Vanguard
- Interface changes addressed in Phase 1a
- All models needed for final design are created and operating
- Adequate design control exists
- Project approval of end item marking

Winding Pack Design

- Requirements/Objectives
- Constraints
- Design
 - CICC Winding Path
 - Insulation Analysis
 - Insulation IR&D
 - 3D Insulation Analysis

Winding Pack Design

- Design of Components
 - Transitions
 - Insulation
 - Ground Wrap
 - He Stubs
 - Impregnation/VPI
 - Coil Leads and Supports

Winding Pack Design

- Comparison to CDR
 - Design Features/Changes
 - Cost
 - Reliability
- Plans

Magnet Interconnections

- Requirements/Objectives
- Constraints
- Design
 - Pre-Assembly of Components
 - Space Allocations
 - Procedures
 - Order of Assembly

Magnet Interconnections

- Design of Components
 - Intercoil Structure (ICS)
 - Case Cooling
 - Bolting Interface
 - CS, PF Interfaces
 - Vertical Support

Magnet Interconnections

- Design of Components
 - Lead Box
 - He Lines
 - Filters
 - Flowmeters
 - He Isolators
 - Splices
 - Component Support

Magnet Interconnections

- Comparison to CDR
 - Design Features/Changes
 - Cost
 - Reliability
- Future Plans

Manufacturing Plan PDR Briefing

The contract requires submission of PDR briefing materials along with the PDR required SDRLs one month prior to the PDR itself. A section of these briefing materials shall include: "a flowchart of operations from receipt of materials through delivery of end items to PPPL, a list of major equipment and tools required at each manufacturing step, exploded views of key process steps, and a list of the verification tests at each step." As part of the process of creating an estimate for Phase II of the TF program we prepared a flow diagram containing the information listed in the requirement. This 11" x 17" fold-out is attached. It shows the major manufacturing and inspection steps, a bill of material for each step and major equipment and tools required for each step. The next level of detail can be found in the draft procedures contained as appendices to SDRL 22 and SDRL 32. SDRL 22 contains details for coil winding, reaction and insulation up through completing of the ground plane operations. SDRL 32 contains the details for the balance of the process including TF case fabrication, installation of coils in the case, potting, and cover welding. Also included are details of the splice between magnets in an octant and preparation and protection of the splice halves for the octant-to-octant splices. Installation of instrumentation is not included since we intend to perform this work after the magnets are installed in the hall in Princeton. These components are delicate and highly susceptible to shipping damage. Information in the SDRLs is broken up into two areas, a written portion which illustrates the high risk operations and risk mitigation plans for each area as well as a description of the various operations and operational sequences of the major equipment used in the steps. Also included are flow schematics containing a greater level of detail than available in the attachment to this document. The test includes a large number of conceptual designs for tooling and equipment as well. The SDRL attachments include detailed draft procedures for each of the main processes making up the entire fabrication sequence.

The attachment is coded. The code for the blocks is shown below: Numbers such as .2 and .46 have no meaning in this chart. They are part numbers and are used for cost collection and roll-up in the estimation process. The block identified as CLOSEQ and shaded is not defined at this time. Additional work may be required at this point to complete the quadrants. This block is acting as a place holder for later definition of this work. Installation support is likewise undefined at this point and is used as a place holder as well.

PROCESS FLOW

Section 4

Manufacturing

4.1.1

TOKAMAK PHYSICS EXPERIMENT
TF MAGNETS

TF Contractor's Preliminary Design Review
September 18-19, 1995

SDRL 37 B

BENDING DEVELOPMENT

RESULTS AND CONCLUSIONS

Presenter: H M BELL

Page 15

Babcock & Wilcox

Bench Bending

- Transitions
 - Turn to Turn
 - Pancake to Pancake
- Leads
 - TF Coils
 - CS Coils

Lead Bending Results

- Springback
- Repeatability
- Coil Set
- Work Hardening
- Easy/ Way vs Hard Way
- Weld Location
- Reaction Cycle Effects

BENCH BENDING TECHNIQUE

- Made 3 or 4 Bends / Sample
- Measured Included Angles
- Plotted Data
- Fitted Least Squares Lines
- Examined Correlation Coefficient

REPEATABILITY

- COMPARED RESULTS FROM:
 - CS 1, 2, 3 6 IN. RADII
 - CS 4, 5 7.5 IN. RADII
 - CS 6,7 9 IN. RADII

CONCLUSIONS:

BENDS ARE REPEATABLE
9 IN. RADII DIE IS MOST REPEATABLE

C/S SPRINGBACK DATA SAMPLE

M/U CS 2 (3' OF IN 908 DUMMY CS CONDUCTOR)

*AS RECEIVED CONDUCTOR

6" DIE

Presenter: H M BELL

Babcock & Wilcox

WELD SEAM ORIENTATION

- COMPARED RESULTS FROM:
– CS 8, 9 7.5 IN. RADII

CONCLUSIONS:

WELD SEAM 90° FROM BEND PLANE CAUSES
GREATER SPRINGBACK

HARD WAY vs. EASY WAY BENDING

- **COMPARED RESULTS FROM:**
 - TF 1, 2 7.5 IN. RADII

CONCLUSIONS:

**SPRINGBACK DIFFERENCE RELATES TO
DIFFERENT BEND ORIENTATION.**

SPRINGBACK / MINIMUM BEND RADIUS

- BEND RADII: 6 IN., 7.5 IN., 9 IN.
- MATERIALS: SS 304, INCOLOY 908, SS 316LN
- 11 PLUS SAMPLES BENT
- EXAMPLE: CS2

CONCLUSIONS:

SPRINGBACK MODEL WORKS

SPRINGBACK IS APPROX. 15 ° (RANGE 12 TO 18 °)

DIE RADIUS < 7.5 IN. UNDESIRABLE

WORK HARDENING EFFECT

- **COMPARED RESULTS FROM PF CONDUCTOR:**
 - PF 1 (AS RECEIVED) $Y=0.8976X+26.47$
 - PF 10 (3 CYCLES ROLL BENDING) $Y=0.8961X+26.566$
- **COMPARED RESULTS FROM CS CONDUCTOR:**
 - CS 6 (AS RECEIVED) $Y=0.8233X+33.996$
 - CS 17 (3 CYCLES ROLL BENDING) $Y=0.8649X+30.695$

ALL BENCH BENDING PERFORMED WITH 9" RADIUS DIE

CONCLUSIONS:

**WORKHARDENING HAS GREATER EFFECT ON
SPRINGBACK OF IN-908 THAN 316LN.**

SDRL-37B

ROLL FORMING

- Machine / Technique
- Data Summary
- Outlook

Section 4.12

Impact of Manufacturing Development and Analysis

Winding Machine Concerns

- Turn Length
- As-Formed Radii
- Build Dimensions
- Coil Restraint
- Cold Work vs Bending
- Reaction Induced Shrinkage
- Access for Lead and Transition Formation
- Helium Stub Weld Access
- Respooling & Rework
- Roll Forming Shrinkage
- Kinks and Twist

Winding Machine Components

- Conductor Payout Spool
- Straightening Rollers
- Roll-Forming Head
- Winding Table & Drive
- Winding Form
- Length Measurement & Twist

Winding Machine (plan view)

Winding Machine (elev view)

Conductor Payout

- 2 Axis of Movement
- 10' Dia. x 6' High Spool Size (TF)
- 5 Layers (1.1 Km)
- Payout Orientation Same as Bending Orientation
- Dynamic Breaking Servo Motor

Conductor Payout (elev)

Straightening Rollers

- Add Cold Work to Conductor
- Respool Conductor
- Straighten Conductor (remove initial bend)
- Can Incorporate Drive Rollers to Cut Machine Cost

Roll-Forming Head

- Pinch Style 5 Roll-Bender
- Side Constraint on Main Bending Rollers
- Added Rolls for Bend Refining and Respooling for Repairs
- Repositioning Controlled by THK Slides and Servomotor Drives on 3 Rollers
- Underhung Above Forming Table
- Last Roller Tangent to Form Location

Roll-Forming Head (plan)

Twist Head

- Operates on Centerline of Conductor
- Imparts Twist Ahead of Forming Between Drive System and Twist Mounted on Trunion
- Twist Needs Determined in Development and Preproduction
- Initial Work Indicates Twist Correction May Not be Necessary

Twist Head (side)

Winding Table

- 3 Eccentricity Located Bearings Provide universal Positioning Capability Within 104" Window
- Servo Motor Control Provides Excellent Table Position Repeatability
- CS and PF Easily Accommodated
- Box Gage for Fixture Control

Winding Form

- Clamps Every 18 Inches Minimize Gaps
- Screw Clamps Hold Conductor In-Plane
- Hydraulic Compression of Vertical Build
- Clearance Provided for Installation of Reaction Compression Rings
- Oversize to Compensate for 0.1% Reaction Shrinkage

Winding Form w/pins

Winding Form w/ compression

Bound Coil for Reaction

Length Measurement

- Rotary Encoder and Rubber Wheel
- Two Systems provide redundancy
- Resolver to Insure Consistent Length Measurement
- Measures Pre-Formed Length
- Developed Length Used to relate Measurements to Turn

Analysis Results

- Pinch Style Roller Provides Straight Feed In of Conductor
- Reaction Force at Primary Roller 11,000 Pounds
- Roll-Former Must be Overhung
- Necessary Range of Motion of Bend Roller 1.5 Inches for Pinch Design

Mfg Development Results (1)

- Conductor Shrinkage 0.1% Must be Added to Winding Dimensions
- Restrained Conductor Does not Relieve During Reaction
- Free Conductor Opens Slightly
- Conductor Requires 10-15% Overbend Depending on Material, Hardness, and Geometry
- TF Hardway Bend Least Overbend

Mfg Development Results (2)

- No Indication of Twist
- Changes in Cold Work or Other Hardness Factors Greatly Affect As-Bent Radii
- As-Bent Length Shorter Than Starting Length: Development Required
- Small Changes in Roll Position Relationship Generate Large Changes in As-Bent Radii: Rigid Repeatable Rolls Necessary

Mfg Development Results (3)

- Turn-to-Turn Transitions Can be Formed by Roll-Former
- Splice Conduit must be Extensively Supported and Restrained to Insure Shape is not Lost During Contraction in Reaction
- Length Measurement is most Important
- Minimize Winding Gaps to Minimize Resin Rich Areas

Helium Stub Attachment & Manual Forming

- **Performed in Air Above Form**
- **Clamps Allow Needed Space**
- **Spacers Retain Conductor in Bend Area**
- **Leads Supported on Form Base Plate**

Reaction Development Results

- Argon Augmented Heat Transfer
 - Time Saving on Heat Up
 - ~ 20 hours at 25°C/Hour to 340°C
 - More Uniform Heating
 - Vacuum 55°C delta across pack
 - Argon 38°C delta across pack

Reaction Development Results

- Copper
 - Saves ~ 5 hours on 185°C Asymptote vs. Stainless Steel
 - Negligible effect on Uniformity

Reaction Development Results

- Dimensional Spacers are subject to Sticking
 - Stainless Steel
 - Copper
 - Incoloy-908
 - Steel

Reaction Development Results

- Heat Transfer is Unidirectional
 - 90% from inner and outer surface
 - 10% from top and bottom surface

Reaction Development Results

- Mass of Coil Cross section vs. Leads
- Poor Conductance of Conduit

Reaction Process Drivers

- Spacers Must Be Coated
 - Boron Nitride
 - Chromium
- SAGBO Concerns
 - Purge Gas Reduces Risk
 - Atmospheric Purity
- Temperature Uniformity

Reaction Process Features

- Cold Wall Box Furnace
 - Vacuum Capability
 - Partial Pressure Capability
 - Internal Heat Exchanger
 - Capacity of 2 Coils of Any Mix
 - Multizone w/ Instrumented Charge

Reaction Process Features

- Auxiliary Heating System
 - More Uniform Heating

Reaction Process Features

- Partial Pressurization System
 - Anticipate ~1 Torr of Inert Gas
 - Argon or Argon/Hydrogen
 - Getter System on Gas Feed

Reaction Process Features

- Conduit Purge System
 - Anticipate $>$ Atmosphere of Inert Gas
 - Helium or Helium/Hydrogen
 - Getter System on Gas Feed
 - Purity Check on Inlet and Exhaust

Reaction Process Reliability Enhancements

- Double Seals on Penetrations
- Redundant Vacuum and Heater Systems
- Backup Power for All Systems except Heaters
- Optional Backup Power for Heaters

Reaction Process Furnace Vacuum Features

- Parallel Vacuum Systems
- RGA/Leak Check Built In
- Monitor on Seal Gap for Leak Detection

Conduit Cleaning Study

- Goal:
 - Evaluate the high strength bond between conduit and VPI resin.
- Experimentation:
 - Survey of cleaning techniques
 - visual inspection
 - compression/shear at room temperature and 77K

Incoloy Coupon Sample

INCOLOY-908 TEST COUPON CONFIGURATION

TEST BUTTON
FOR
COMPRESSION SHEAR TEST

Cleaning Methods

1. Alcohol wipe (control)
2. Chemical etch HC1
3. C O 2 blast
4. Al 2 O 3 blast (220 grit) & C O 2 blast
5. Scotchbrite & alcohol wipe
6. Al 2 O 3 flap wheel (120 grit) & air blow off

Cleaning Methods Con't

- 7. Al 2 O 3 flap wheel & C O 2 blast**
- 8. Si /C nylon filament wheel & air blow off**
- 9. Si /C nylon filament wheel & C O 2 blast**
- 10. Al 2 O 3 Wheel medium buff blend & air blow off**
- 11. Al 2 O 3 wheel medium buff blend & C O 2**

Compression/Shearing Test

Conduit Cleaning Results

•	Compression/Shear Strength		
•	(PSI)		
•		Room Temp	77K
•	Control	4317	8800
•	Acid Clean	7257	11374
•	120 Grit Flap Wheel	4969	6587
•	80 Grit Filament Wheel	4110	5555

Conduit Cleaning Study

Conclusions:

- Consistent high strength bond can be achieved with available mechanical cleaning techniques
- Cryogenic temperature (77K) enhances bond strength

Westinghouse /B&W Baseline Insulation System

Turn-to-Turn/

Pancake-to-Pancake:

2 layers of polyimide (.001 "), 48% overlap

1 layer of 3-D S2 fiberglass (.014 "), 48%
overlap

Corner Roving:

3-D S2 triangular fiberglass preform

Insulation System Con't

Ground Wall Insulation:

- VPI 1-2 layers of 3-D S2 fiberglass (.014 "),
48% overlap
- VPI 2-2 layers of 3-D S2 fiberglass (.014 "),
48% overlap

Conductive Shield:

- 1 layer of aluminum crepe, 5% overlap

Insulation System Con't

Shield Insulation:

1 layer of 3-D S2 fiberglass (.024 "), 48%
overlap

VPI Resin: Shell 826

Tactifier: Shell 1007 F

Base Tank Potting Resin:

Tentatively-alumina filled epoxy
STYCAST 2850FT

Insulation System

Insulation Research and Design

Goal:

- Evaluate the performance of 3-D fiberglass insulation
- Compare the results to the existing 2-D fiberglass insulation.

Insulation Research and Design

Experimentation:

- Fabricated 3x3 matrix samples
- Vacuum Pressure Impregnated and cured
- Electrical and mechanical compression/
shear testing

Insulation Mock-up Sample

I R & D Fixtures

COMPRESSION FIXTURE

CURING FIXTURE

IR & D Fixtures

shearing fixture

Insulation Research and Design

Results:

- Samples consisting of 3-D fiberglass failed at higher loads in the compression/shear testing
-

Coil -Set up for VPI

- Coil Pack Fixturing 1
- Transporting 17
- Turn Separating Set up 2,3
- Wrap Head Set up 6,7
- Cleaning & Testing
- Assemble & set up VPI mold 9,10
 - Spacer
 - Insulation

Coil Pack Insulation

- Apply Turn and Pancake Insulation
 - Lower Coils 5
 - Insulate 8,9
- Testing
- Insert 3D Corner Roving
- Insert preformed void fillers
- Insulate & Seal helium stubs 13
- 1st VPI Cycle 11

Grd. Plane Insulation-VPI

- **Prepare Surface**
 - Remove risers, flashings, round corners
- **Apply ground plane insulation** 16,4
- **Apply conductive wrap** 4
 - Insulate gaps -2 locations 12
 - Attach leads 18
- **Insulate and seal**
 - Leads & nozzles 13,14,15

Why 2 VPI Cycles

- 1st VPI
 - 1.) Preparing foundation
 - Main Ground Plane Ins. (GPI)
 - Conductive shield wrap
 - 2.) Finishing and curing
 - Turn to turn insulation
 - Pancake to pancake insulation

VPI Cont.

- 2nd VPI
 - 1.) Finishing and curing GPI
 - 2.) Bonds Electrostatic Shield
 - 3.) Finishes & Cures shield to grd. ins.
- 1st vacuum potting
 - Accurately holds coil position
- 2nd vacuum potting
 - Completes encapsulation

Coil Clamp Ring

2

Coil Support Structure

GRAPHIC

Turn Separating Fixture

NOTE: SPACER PLATES OMITTED FOR CLARITY.

CLAMP HOLDING RODS

Coil Pack Cross section

Coil Pack Ins. Process

Wrapping Cart Track

Wrapping Side View

7 9

Wrapping Head

GRAPHIC

46

Wrapping Cart

VPI Mold

VPI System

SCHEMATIC OF VPI SYSTEM

12

Shield Gap

GRAPHIC

Helium nozzle Ins.

Conductive Preform

Lead Ins. & Seal

GRAPHIC

Wrapping Coil Pack

GRAPHIC

Conductive Shield Leads

GRAPHIC

4.4 Magnet Assembly

4.4.1 CASE STRUCTURE

- **Simplifications for Cost Reductions**
- **Development Mock-ups**
- **Fabrication Outline**

Simplifications To Reduce Cost

- **Fabrication of Coil Case From Rolled Plate**
- **Use of G-10 Locator Pads Reduces Precision Machining Requirement in Coil Case Interior**
- **Stress Relief Reduces Final Machining Stock Removal**

Development Mock-ups

- Weld Development Mock-ups
- 1/4 Scale Mock-up of TF Case
- Machining Mock-ups

Fabrication Outline

- Coil Case Rolling
- Assemble and Weld Cases to Central Forging
- Weld ICS
- Insert Cooling Tubes, Weld Tabs
- Weld ICS Cover
- Machine Fiducial Interface
- Attach Fiducials

Fabrication Outline (cont.)

- Machine Case
- Anneal
- Attach G-10 Locator Pads
- Survey Case
- Final Machine Pads & Case

4.4.2 Coil Insertion and Assembly

- Coil Preparation
- Coil Insertion
- Partial Potting of Coil in Case
- Coil Cover Assembly
- Case Elevation & Potting
- Coil Orientation Tracking & Control

Coil Preparation

- Inspection Of Coil
- Attachment Of Locator Pads
- Final Handwork of Pads to Achieve Final Dimension
- Final Inspection

Coil Preparation

Coil Preparation Station

4.4.2 Coil Insertion and Assembly

Coil Insertion

Partial Potting

- Locks Coil into Ideal Location
- Provide an Opportunity to Do As- Potted Inspection for As- Built Database

Coil Cover Attachment

- Bolted vs. Welded Cover
 - Welding Distortion vs. Problems with Bolting
- Track Welding System

Case Elevation and Final Potting

Coil Location Tracking & Control

Jeremy VandeBogart

4.4.3 Octant Assembly

- **Splice Installation**
- **Chimney Assembly**
- **Instrumentation**
- **Final Machining**
- **Advantages of Trial Assembly of Octants**

Splice Installation

- Done with Leads in Vertical Orientation
- Consistent with Current Splice Design
- Minimizes Risk to Case

Chimney Installation

- Bolted vs. Welding Chimney Sides, Front, & Back
- Finishing Stubs, Grounding Electrostatic Shield, Instrumentation
- Final Machining - Mt. Vernon Works
- Trial Assembly of Octants

Benefits of Octant Trial Assembly

- Assembly on Milling Center Allows on Machine Inspection
- Final Machining of Splice Terminators Allows Alignment of Octant to Octant with Minimum Stress on Leads
- Any Problems are Identified Early and Can Be Corrected Quickly
- Minimized Impact on PPPL Facility

Section 4.5 Preliminary Manufacturing Plan

Flowchart / Work Location

Process Development (1)

- **Winding Machine Testing & Qualification**
- **Insulation Application & Impregnation**
- **Nozzle Attachment**
- **Case Welding and Distortion**
- **Case Cover Installation**
 - **Bolting vs. Welding**
- **Splice Preparation and Installation**

Process Development (2)

- **Instrumentation Installation**
- **Reaction Furnace Testing & Qualification**
- **Hydraulic Connection Install & Weld**
- **Inspection Development**
 - **Positional Transfer**
 - **Conduit Crack Inspection**
 - **Eddy Current Conduit Location**

Long Lead Items

- TF Octant Case and Covers
- Winding Machine
- Reaction Furnace
- VPI System and Forms
- Phase II GFM

GFM Requirements

- **TF Dummy Conductor for Testing**
- **TF Dummy Conductor for Machine and Process Qualification**
- **TF Dummy Conductor for Deliverable End Items**
- **TF Conductor for Machine / Process Qualification**
- **TF Conductor for Deliverable End Items**

Process Time Estimates

- Turn Winding
- Turn Insulation
- Reaction
- Nozzle Attachment
- Case Installation
- VPI Process (once thru)

Shipping and Handling

- TF Octant Case - NNFD to Mt Vernon and Back
- TF Octant to Princeton
- TF Quadrant to Princeton

TPX TF Magnet Assembly

**FAILURE MODES, EFFECTS AND
CRITICALITY ANALYSIS**

(FMECA)

SDRL 23

Overview

- A. Purpose
- B. Approach
- C. Reliability Allocation
- D. Planned Actions
- E. Summary

A. PURPOSE

To determine, evaluate, and minimize risk areas in achieving RAM goals.

To serve as a communication vehicle of failure modes, causes, and controls/mitigation between the organizations.

To focus the program's efforts where they will do the most good.

B. APPROACH

- I. Define the RAM risk.**
- II. Prioritize organization's efforts.**
- III. Mitigating Actions.**

I. Defining the RAM risk.

- Identify Failure Modes.
- Identify Causes.
- Likelihood of Occurance (Probability).
- Significance of Failure (Severity).

Sources of information

- FMECA meetings.
- IPT meetings (Design, Manufacturing, QA, Test).
- General Atomics (knowledge and experience of running the DIII-D tokamak).
- Historical magnet failure databases.
- One on one exchanges with the various organizations.
- Other program's FMECA's.

FMECA Meetings

Scope: - TF Magnet Assembly
 - Design and Process Issues

Number: - 8 @ B&W
 - 1 @ GA

Representation:

- Design	- Test
- Systems	- Quality Assurance
- Manufacturing	

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.

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.

II. Prioritize organization's efforts

Focus on critical failure modes.

Critical Failure Modes List: a "watch list" that serves for special attention by program management and engineering.

Focus effort on removing items from list, mitigating actions: Design changes, QA controls, tests and reliability analysis.

List will remain responsive to newly identified RAM risk areas.

Criteria for Critical Items

		PROBABILITY OF OCCURRENCE				
		A	B	C	D	E
S E V E R E C R I T I C A L 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

TPX TF Magnet Assembly FMECA Process

Continuous Iterative Design/Analysis/Planning Tool

FMECA Sheet (Example)

Item No. TFQD2/a 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 ...)								

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 TFQD22B\ a TFQD32A\ a TFQD32C\ b	II-C	Conduit He leak- leading to arcing/short within coil. He stub weld failure, leading to leak, short. He lines/He isolator leak - leading to arcing/short within TF Lead Box.
TFQB1\ a TFQC1\ a TFQD31A\ a TFQD32C\ a	II-C	Shorted He Isolator
TFQD\ a TFQD2\ a TFQD42\ c	II-C	Excessive field errors; misalignments.

III. Mitigating Actions (Example)

TFQD22A1\ a	Superconductor - Unable to meet or sustain the operating current.
--------------------	--

- 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 by the Manufacturing 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 documentation to ensure all relevant processes were in control at the time of delivery of the CICC to B&W. 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.
- 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
- 6) Cryogenic test at octant assembly level is recommended, and is incorporated into the "TF Magnet Acceptance Test Plan", TPX-PLAN-ATP. Many 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. 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.
- 7) Design will 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. Current plans call for dedicated splice supports - details in Phase II.

C. RELIABILITY ALLOCATION.

Objectives: Practical solution to unbounded question.
Avoid numbers game, output must be value added.

Approach: Generate Allocation

Provide Prediction Methodology

Calculations will be performed on a
prioritized fashion

Critical Items

Potential Critical Items

Critical List: payoff exists for complex analysis.

TF Magnet System Reliability

D. PLANNED ACTIONS

Prior to PDR:

- Address any SDRL/CPDR comments.
- Update FMECA.
- Develop preliminary quantitative FMECA/ RAM allocations/predictions.
- Provide assessment of compliance to A-spec RAM allocation.
- Other RAM tasks.

E. SUMMARY

FMECA:

A team effort (design, systems, manufacturing, test, and QA.

CPDR design incorporates many features to enhance system availability.

CDR multiple coil lead configurations replaced with single coil lead configuration. Helps manufacturing, and spares planning/procurement.

SUMMARY

TF lead box-bolted type, components laid out to provide good access for repair actions.

Tests have been recommended and incorporated into the test plans.

Many "potential critical items" in the FMECA - reassess in Phase II.

TF Materials and Processes Selection (SDRL 21)

TF Materials and Processes Selection

- Identification of candidate materials and manufacturing processes for TF Magnet components
- Justification of selections
- Development of supporting properties database

TF M&P Database

- Developed using Microsoft Access
- Supports addition/deletion and sorting of materials and properties (mechanical/thermal)
- Organizes component/material assignment data
- Stores manufacturing process information including process selection criteria and rationale
- Provides report development capability for all data

Materials Selection

- SS 316LN and Incoloy 908 properties from TPX Material Properties Handbook
- Insulation material properties from 14-950605-WEC-FRoach-01 memo
- Other materials data provided to Materials Committee for review:
 - Aluminum crepe (winding pack ground plane insulation)
 - Inconel 625 filler metal (welding)
 - Copper OFHC (reaction process spacers, cooling loop tubing)
 - Ultem 2300 (bolts for internal lead box supports)
- Selection criteria and rationale included for each material

TF Materials/Parts Data

- Parts list based at octant level
- Materials assigned to each part
- As TF design matures, database will be updated accordingly

TF Process Selection

- Several major manufacturing processes incorporated into database
 - TF Coil Winding
 - TF Coil Cleaning, Insulation and VPI
 - TF Coil Reaction
 - TF Case Assembly
 - TF Welding
- Brief description of process, conditions, process location, and special cautions included in database
- Selection criteria and rationale provided for each process

TF Materials and Processes Selection Report

- Preliminary document drafted August 1995
- Summarizes selection activity
- Includes complete database reports:
 - Material Properties Report
 - Parts/Materials Report
 - Processes Report
- Database and document to be updated as TF design effort continues in next phase

Quality Assurance & Test Requirements

Annex 1

<u>SOW</u>	<u>Requirement</u>	<u>Compliance</u>	<u>Status</u>
V.4	Quality Assurance	SDRL 13	Approved
1.3.11	Coil Verification Testing Plan	SDRL 33	Submitted 8/18/95; FDR
1.3.12	Material & Component Testing Plan	SDRL 34	Submitted 8/18/95; FDR
1.3.18	Acceptance Test Plans	SDRL 45	Submitted 8/18/95; FDR
3.3.12	Prototype Test Plan	SDRL 35	Phase 2 + TBP; FDR

A&MS Quality Assurance

- QA Plan Meets Requirements:
 - DOE Order 5700.6C
 - TPX LLNL QA Plan
- Systems Implemented
- ISO 9001 / MIL-Q-9858A, NR Tradition
- ASME “U” and “R” Stamps

Quality / Test Plans

- Manufacturing, Inspection, & Test Flow Diagrams (MITFD)
 - Process Flows
 - Major Mfg., Test, and Inspection Operations
- Integrated Flow Between Plans
- Integrated with Manufacturing Operations

Materials and Component Testing

Chris Rey

Outline

I. M. & C. Test Definition / Requirements

II. M&C Tests

- welds
- electrical insulation
- chimney
- splice

III. Future Work

M&C Definition/ Requirements

M&C Definition: provide information to validate component selection, design analyses, manufacturing processes, and test methods.

M&C Requirements:

- Structure & Design Criteria Document (TPX-STND-001)
- General requirements document (GRD)
- SOW
- SRDL's-13 (QA), 20 (TF spec.), 23 (FMECA) 33 (CVTP), 45 (ATP)

M&C Testing

Sub-scale:

- manufacturing weld mock-ups
- trial windings (lead bending, forming, etc.)
- ? x ? insulation mock-ups
- splice joint process development
- bench top: voltage tap & fiber optic

Large Scale:

- dummy coil

M&C Testing

Major M&C Testing:

- materials
- welds
- flow testing
- splice testing & Nb₃Sn (TPX testing)
- chimney
- insulation
- instrumentation- v-taps, fiber-optics, strain
- leak testing

M&C Testing

1. **Materials:** are materials selected for use in TF magnets, well characterized---no tests planned!
2. **Welds** (He stub on In 908, case closure& chimney 316 SS w/ In 625 filler, etc.)
 - A. Helium Stub Attachment
 - process parameter development (CICC temp. profile)
 - LN₂ cold shocking & subsequent leak detection
 - Die penetrant
 - UT inspection (verification of method)
 - Destructive Evaluation via sectioning w/ X-ray

M&C Testing

3. Electrical Insulation:

- process control verification
- pin-hole detection on dry wrap
- low voltage: resistance/unit length (pre/post reaction), inductance & quality
- High voltage: dc hipot, induced voltage, impulse, Tan δ evaluation, high resistance
- voids/resin rich detection: Tan δ , destructive evaluation
- life-time testing: thermal cycles, HV electrical cycles, HV to failure, cyclical stress, radiation (TPX project)

M&C Testing

4. Chimney Isolation:

- electric field stress analysis
- manufacturing tolerance evaluation
- hipot (failure) in vacuum
- hipot (failure) vs He concentration level--> He gas temp (worst case). 300, 77, or 20-30 K

M&C Testing

5. Splice Joint (TPX conceptual design):

- splice/lead extraction configuration.
- splice resistance
- leak tightness
- UT evaluation of %solder bond
- life-cycle

Nb₃Sn Evaluation (TPX test facility):

- vendor process control
- extracted strand I_c (T,B, ϵ) evaluation reaction

M&C Testing Future Work

- coordinate w/ FMECA, QA Plan, Manufacturing
- specify facilities & equipment
- establish pass/fail criteria for ATP, CVTP
- train personnel
- write detailed test procedures for ATP, CVTP

Coil Verification Testing

Chris Rey

Outline

I. Test Requirements

II. Test Matrix

III. MIFAB

IV. Coil Verification Testing

- Insulation
- Welding
- Process Control

V. Future Work

TPX Coil Verification Testing

Coil Verification Definition: all the room temperature tests, inspections, and process control verification performed on the individual TF coils prior to installation into the TF magnet assembly.

Coil Verification Test Requirements:

- General requirements document (GRD)
- Statement of Work (SOW)
- SRDL's-13 (QA), 20 (TF spec.), 23 (FEMECA) 33 (CVTP), 45 (ATP)

Test Matrix

ATP Par.	TFMSRD Par.		Analysis	Demo	Inspection	Test	N/A
	3.2.3	Reliability and Availability	x				
	3.2.4	Maintainability		x			
	3.2.5	Environmental Conditions					x
	3.2.5.1	Shipping and Storage Environments	x	x			
	3.2.5.2	Operating Environments	x				
	3.2.6	Transportability		x			
	3.3	Design and Construction					x
	3.3.1	Materials, Processes, and Parts					x
	3.3.1.1	Material Selection		x			
4.7, 4.8	3.3.1.2	Weldments	x		x		
	3.3.2	Reserved					x
QA Plan	3.3.3	Nameplates and Product Marking			x		
QA Plan	3.3.4	Workmanship			x		
	3.3.5	Interchangeability of Components		x			
	3.3.6	Safety		x			
	3.3.7	Human Factors		x			
	3.3.8	Structural Integrity					x
	3.3.8.1	TF Magnet Structures	x				
	3.3.8.2	Support Equipment	x				
	3.4	Documentation					x
	3.4.1	Specifications			x		
	3.4.2	Design Drawings			x		
	3.4.3	Plans			x		
	3.5	Logistics					x
	3.5.1	Maintenance		x			
	3.5.2	Supply		x			
	3.5.3	Facilities and Facility Equipment		x			
	3.6	Personnel and Training					x
	3.6.1	Personnel		x			
	3.6.2	Training		x			
	3.7	Major Component Characteristics					x
Coil Verification Test Plan 6	3.7.1	TF Magnet Coil	x			A, P, S	
4.3, 5, 6	3.7.2	TF Magnet Structure	x			S	
5, 6	3.7.3	TF Local Instrumentation and Control		x		A, S	
	3.7.4	TF Bus and Leads	x	x		S	

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

Presenter: C.M. Rey

Page 7

Lock & Wilcox

TPX MIFAB

Coil Verification Testing

Process Control Verification:

- Parameter control development (cal. of equipment, No. of samples, etc.)
- Materials certification
- Personnel qualification
- Inspections & tests (dimensional, visual, NDE, DE, etc.)

Coil Verification Testing

Insulation (TFMS 3.2.1.1 & 3.2.2.3):

A. Turn to Turn, Layer to Layer:

- pin-hole detection (in-line--> pre VPI)
- HV impulse- pre VPI reduced V, post VPI ~2900 V
- HV Induced voltage
- LV resistance & inductance

B. Coil to Ground

- dc hipot 16 kV ($2 \cdot V_{op} + 1\text{kV}$)
- high resistance
- Tan δ (investigate cost/benefit)

Coil Verification Testing

Leak Detection:

- He leak check components (flow kit, fittings etc.--> sensitivity $\sim 3 \times 10^{-9}$ atm-cm³/s)
- He leak check stub welds (post reaction pipe conductance--> virtual leak ??)
- CICC leak detection back-up: Pressurize conduit-
 - a) bubble test (gross leaks)
 - b) sonic detection
 - c) gas sniffer

optimize sensitivity: background noise/gas, conduit pressure, sensing distance, gas species, geometry dependent

Coil Verification Future Work

- Further coordinate with QA Plan (13), FMECA (23)
- Establish pass/fail criteria based on M&C testing
- Determine facility & equipment requirements
- Write detailed test procedures
- Train technicians

TPX Acceptance Testing

Chris Rey

Outline

- I. Acceptance Test Definition Requirements
- II. Test Matrix
- III. MIFAB
- IV. Testing
- V. Octant Level Cold Test
- VI. System Level Cold Test
- VII. Future Work

Definition/Requirements

TF Acceptance Testing: all tests, inspections, and process control parameter verification that are performed on the TF magnets after installation into the TF magnet assembly all the way to and including Tokamak system level cold testing.

TF Test Requirements:

- GRD
- SOW
- SRDL'S--> 13 (QA), 17 (TFMS), 23 (FMECA), 32 (TF Assembly) 33 (CVTP), 34 (MCTP)
-

**TOKAMAK PHYSICS EXPERIMENT
TF MAGNETS**

**TF Contractor's Preliminary Design Review
September 18-19, 1995**

Test Matrix

ATP Par.	TFMSRD Par.		Analysis	Demo	Inspection	Test	N/A
	3.2.3	Reliability and Availability	x				
	3.2.4	Maintainability		x			
	3.2.5	Environmental Conditions					x
	3.2.5.1	Shipping and Storage Environments	x	x			
	3.2.5.2	Operating Environments	x				
	3.2.6	Transportability		x			
	3.3	Design and Construction					x
	3.3.1	Materials, Processes, and Parts					x
	3.3.1.1	Material Selection		x			
4.7, 4.8	3.3.1.2	Weldments	x		x		
	3.3.2	Reserved					x
QA Plan	3.3.3	Nameplates and Product Marking			x		
QA Plan	3.3.4	Workmanship			x		
	3.3.5	Interchangeability of Components		x			
	3.3.6	Safety		x			
	3.3.7	Human Factors		x			
	3.3.8	Structural Integrity					x
	3.3.8.1	TF Magnet Structures	x				
	3.3.8.2	Support Equipment	x				
	3.4	Documentation					x
	3.4.1	Specifications			x		
	3.4.2	Design Drawings			x		
	3.4.3	Plans			x		
	3.5	Logistics					x
	3.5.1	Maintenance		x			
	3.5.2	Supply		x			
	3.5.3	Facilities and Facility Equipment		x			
	3.6	Personnel and Training					x
	3.6.1	Personnel		x			
	3.6.2	Training		x			
	3.7	Major Component Characteristics					x
Coil Verification Test Plan 6	3.7.1	TF Magnet Coil	x			A, P, S	
4.3, 5, 6	3.7.2	TF Magnet Structure	x			S	
5, 6	3.7.3	TF Local Instrumentation and Control		x		A, S	
	3.7.4	TF Bus and Leads	x	x		S	

Presenter: C.M. I

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

& Wilcox

MIFAB

Figure 3.3.3-3 TF Magnet Factory Assembly and Acceptance

Acceptance Testing

Instrumentation:

Measurement	Type	Type of Test
Voltage Taps	Co-wound Coax. Inductive - TBD	continuity, dc resistance, inductance (inductive type only), insulation integrity, time domain reflectometry (TDR see ref. No: 14)
Strain Gages	TBD	continuity, dc resistance, insulation integrity, calibration
QD fiber optics	TBD	optical time domain reflectometry (OTDR)
He flow sensors	TBD	continuity, insulation integrity, calibration
Temp. sensors	Cernox	continuity, insulation integrity, calibration

Octant Level Cold Testing

Purpose: First opportunity for cold testing. Could identify critical failure mode--> TF magnet unable to reach design current & magnetic field. Significantly reduce program risk & cost in event of failure once installed.

Objectives:

- verify fab. & assembly of 2 coils, cases, and structure
- verify conductor properties
- verify coil diagnostics & instrumentation
- cryogenic parameters. (cooldown time, temp profile, etc.)

Octant Level Cold Testing

- verify leak tightness of coils & structure
- verify cryogenic flow characteristics
- quench performance
- verify quench detection system
- verify electrical insulation
- measure joint resistance
- case cooling simulation
- TF structure characteristics

System Level Cold Testing

Purpose: First opportunity to verify operation of all coils (TF, PF, CS, corr.) as a system.

Objectives:

- verification of magnetic field errors (ripple, harmonics)
- verification of quench & QDS performance
- correction coil verification
- cryogenic parameters (cooldown, warm-up, temp profile, etc)
- insulation integrity
- structural characteristics
- etc.

Future Work

- Further coordinate with QA Plan (13), FMECA (23), Alignment (32) CVTP (33)
- Establish pass/fail criteria based on M&C testing
- Determine facility & equipment requirements
- Write detailed test procedures
- Train technicians

Planning Tools

- Integrated Planning (Cobra, Open Plan)
 - Work Definition
 - Scheduling
 - Cost Estimating (Integrated Cost/Schedule)
 - Baseline Development
- Excellent Phase I System Improved
- Yields timely and economical response to LLNL/PPPL/DOE Funding & Technical needs

Key Plan Objectives

- Meet LLNL/PPPL Schedule Needs
- Minimize Equipment & Tooling Cost
- Maximize use of equipment & Facilities
- Deliver Quality Product

Critical Path Issues

- **Advance Equipment Design**
 - Winding Machine
 - Reaction furnace
- **Prototype Magnet Fab & Test**
- **Wind Quad 1, Reaction, Assembly**
- **Case Process & Tooling**
- **Long Lead & GFM Materials**

Critical Equipment

- Winding Machine
- Reaction Furnace
- Case Fabrication (Available)

Key Process Assumptions

- 2.5 coil turns per shift
- 3 Shifts / 5 days per week
- One Winding Machine
- One Reaction Furnace
- 100% Coil Yield

Key Milestones

- Contract Start 5/15/96
- FDR 2/3/97
- PRR 1/15/98
- Prototype Testing 2/15/98
- Production Start
- First Coil Complete 3/30/98
- Delivery
- First Quad Delivered 3/23/99
- Last Quad Delivered 10/19/99

Integrated Schedule

- Reference: SDRL 36 Integrated Magnet Plan (Schedules)
 - Copies of SDRL 36 Schedules will also be available for presentation at PDR.

NEW CONTRACT REVENUE REPORT		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT		DATE		PAGE	
CONTRACT NO.		BUSINESS UNIT					

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.