PPPL
PRINCETON PLASMA PHYSICS LABORATORY

FIRE TF, PF, and Structures Cost Estimates

Presented by P. Heitzenroeder for the FIRE Team

FIRE Fusion Ignition Research Experiment

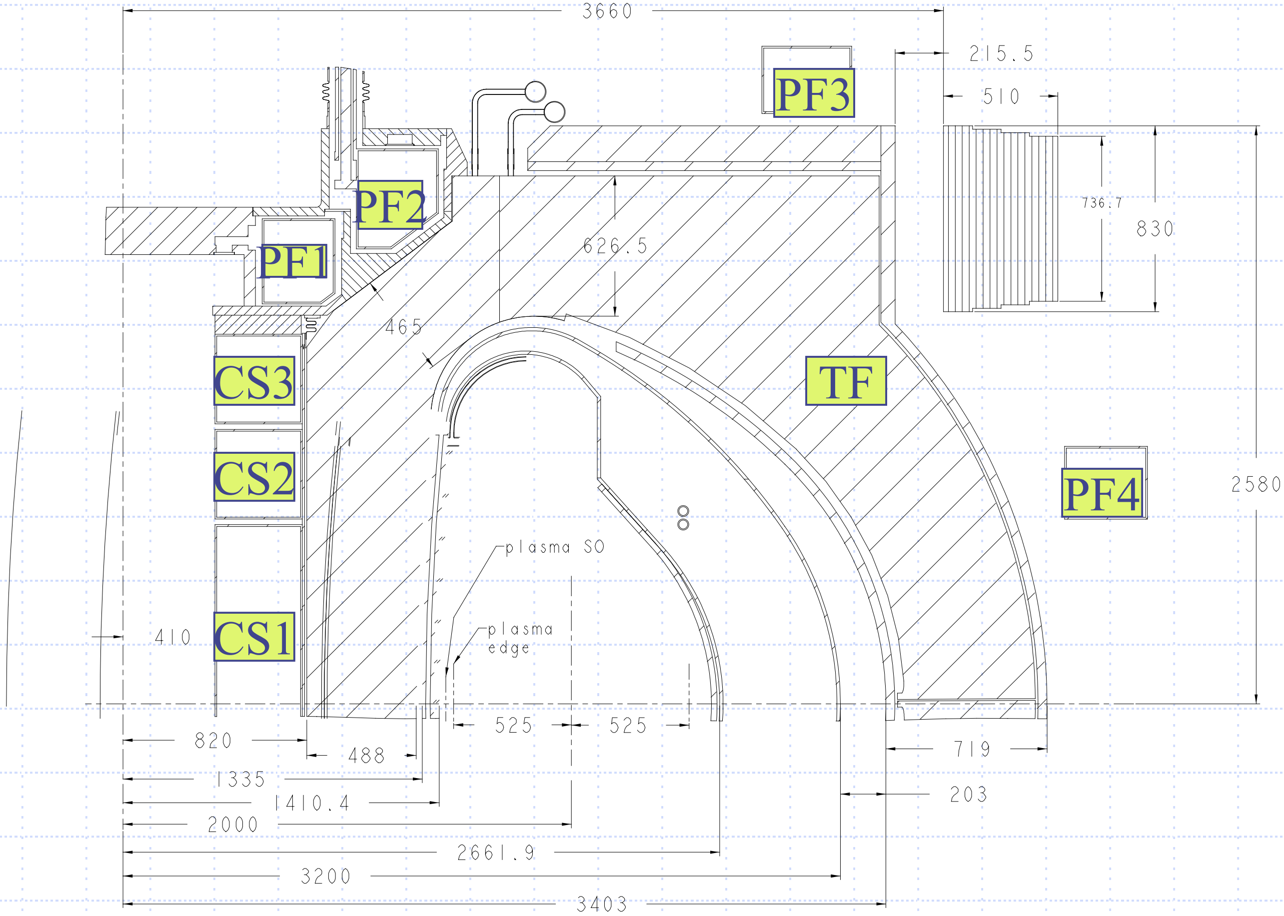
Costing Methodology for the FIRE Coils and Structures

- **Preliminary specifications were developed to guide the costing process for the TF and PF coils. These were based on the recently constructed NSTX machine and contained “typical” inspection and reporting requirements.**
  - 11-990615-12: FIRE PF Coil Copper Specification
  - 11-990615-12: FIRE TF Coil Copper Specification
  - 11-990615-05: Draft Specification for FIRE Center Stack and Ring Coils
  - 11-990615-03: FIRE Specification for Preconceptual Costing of the Toroidal Field Coils

Cost Estimating

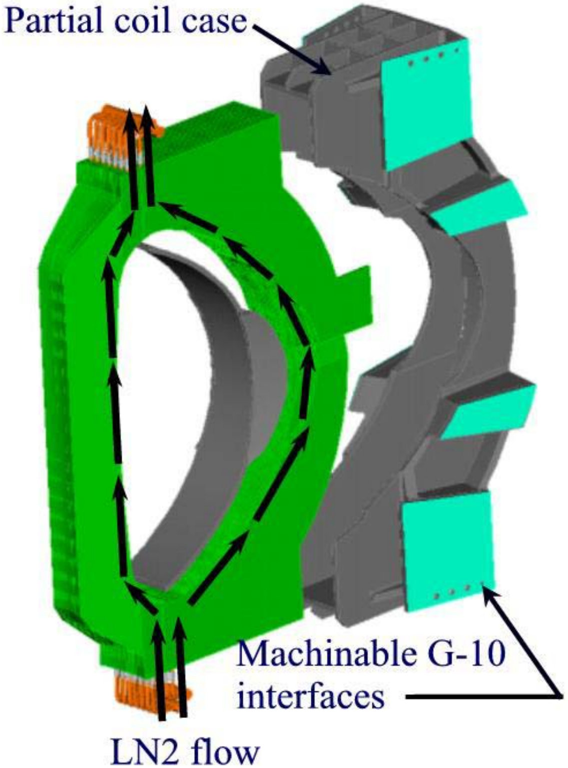
- **Cost estimates for the TF and PF coils were developed by Advanced Energy Systems (AES)**
  - Used a combination of budgetary cost estimates from industry and internal estimates based on their experience with similar items.
- **Cost estimates for most of the structures were developed by Boeing.**
  - Also used a combination of budgetary estimates and internal estimates.
  - PF support estimates were prepared by Peter Titus
- **Cost estimates for the field error correction coils were scaled from the TPX design, which used 12 "picture frame" type coils.**

FIRE TF and PF Coils



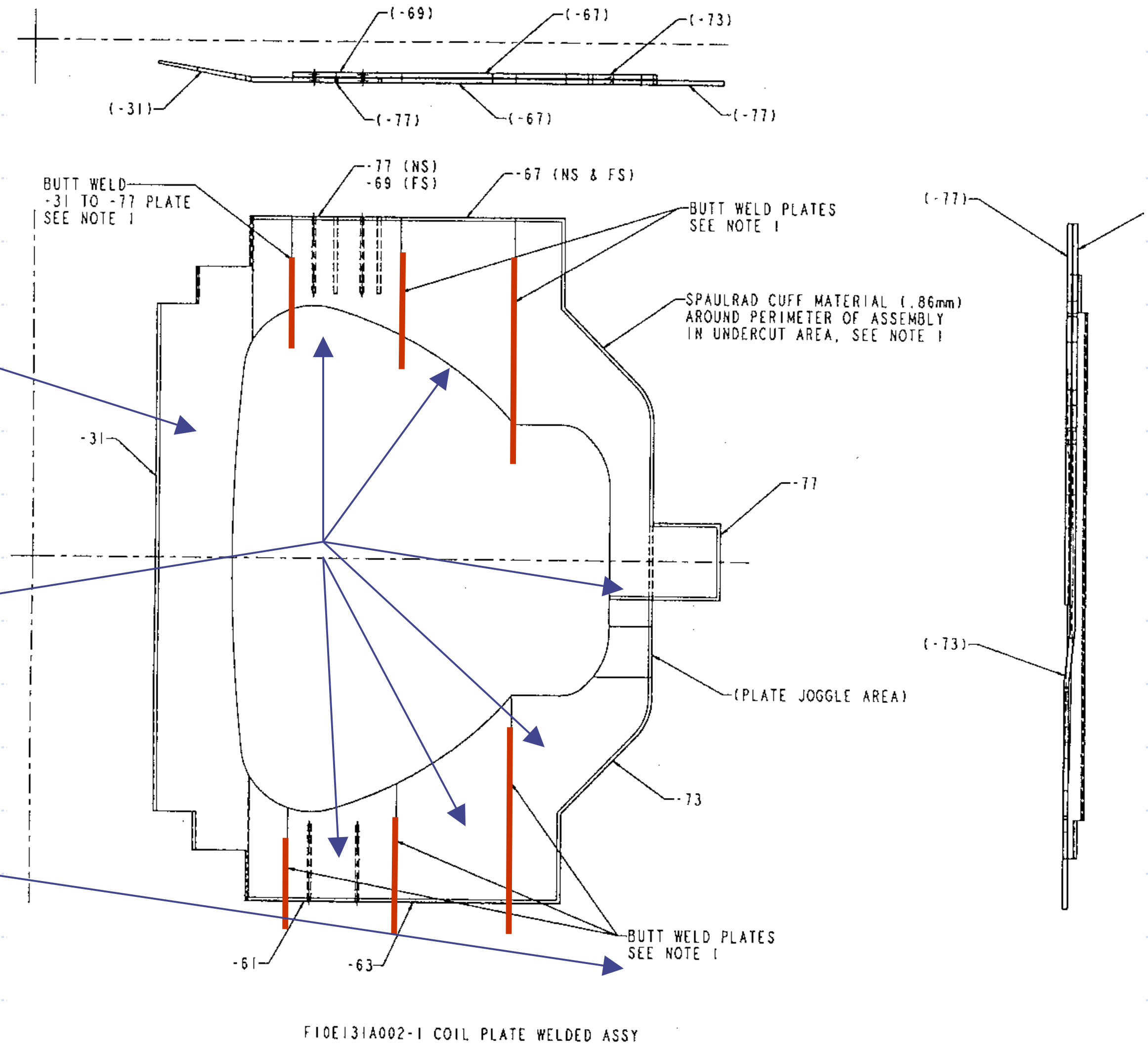
TF Coil Design

- Partially cased, wedged design
- 16 coils; 15 t/coil
- Peak current: 417 kA @10T
- Radially oriented plates similar to BPX
  - C17510 BeCu inner leg
  - C10200 outer leg
- LN_2 inertially cooled



TF Plate Construction

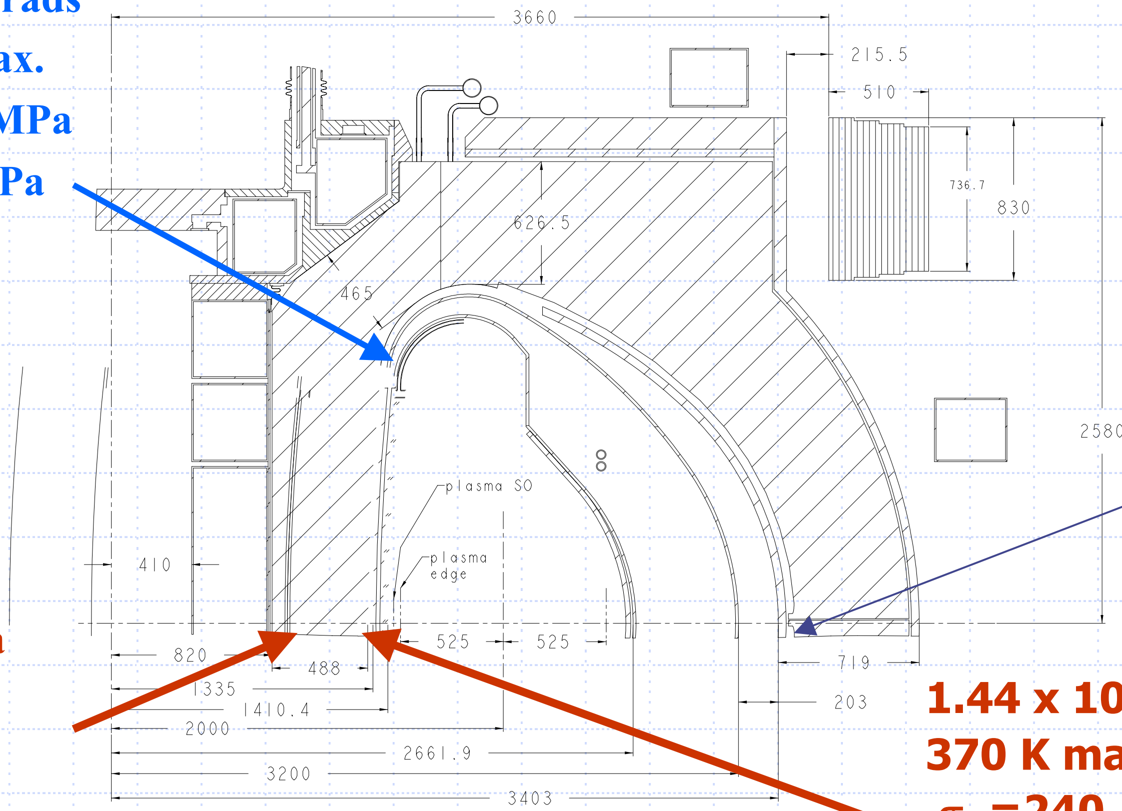
- C17510 BeCu – 68% IACS; σ_y=724 MPa; σ_u=800 MPa.
- C10200 OFHC 100% IACS; σ_y=200-300 MPa; min. elongation of 12%.
- Segments jointed by e-beam or friction stir welds.



TF Insulation Requirements

(Values are for 10T / 12T)

3.9×10^{8} rads
252 K max.
σ_c =179 MPa
σ_{VM}= MPa



1×10^{7} rads
172 K max.
$\sigma_{c\sim}$~100 MPa

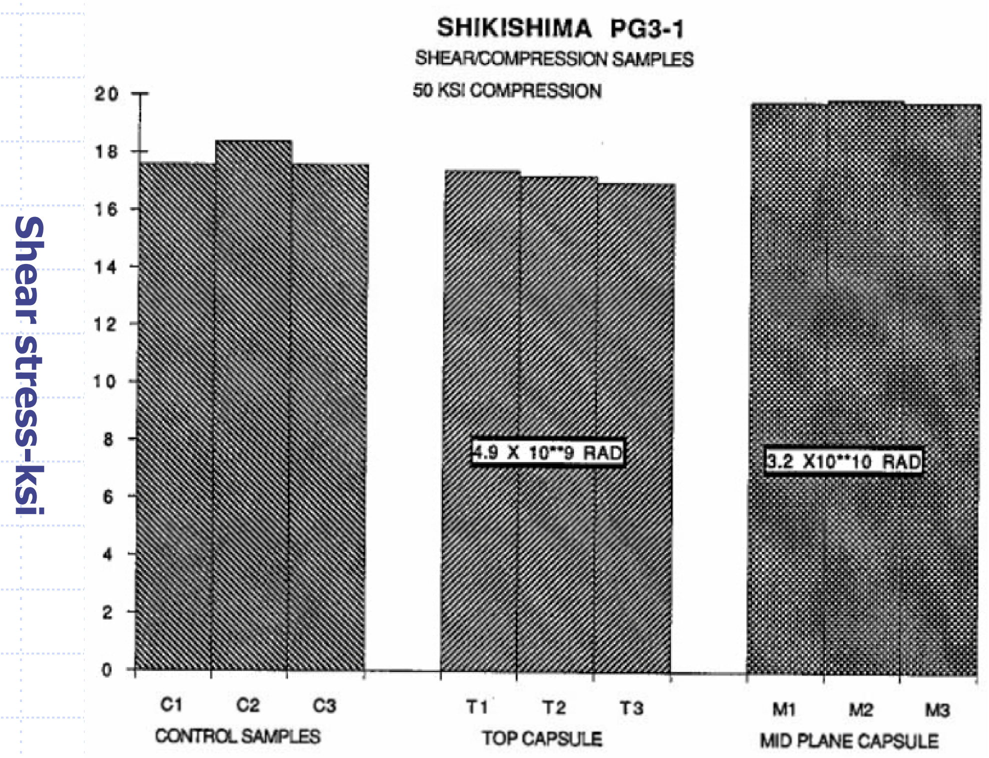
σ_c =360 MPa
σ_{VM}=469 / 689MPa

1.44×10^{10} rads
370 K max.
σ_c =240 / 346 MPa
σ_{VM}=300 / 440 MPa

Temperature excursion: Inner leg: 80-373 K

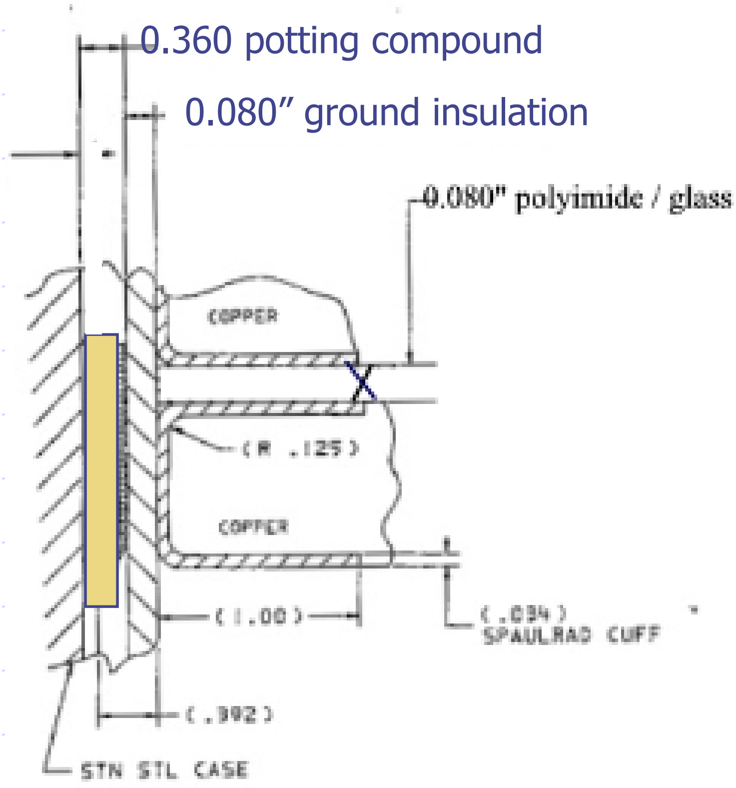
Available Epoxy/Glass Has Adequate Radiation Resistance

- Test data from CIT indicates several epoxy/glass materials have more than adequate radiation resistance.
- We plan to support SBIR's that are working on high radiation resistance insulating materials with good processing properties to possibly permit life extension.



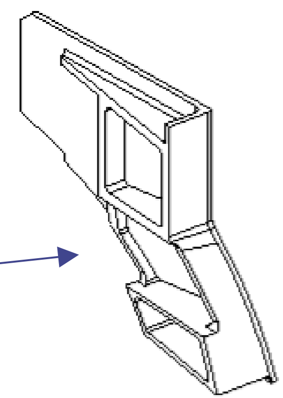
TF Insulation Details

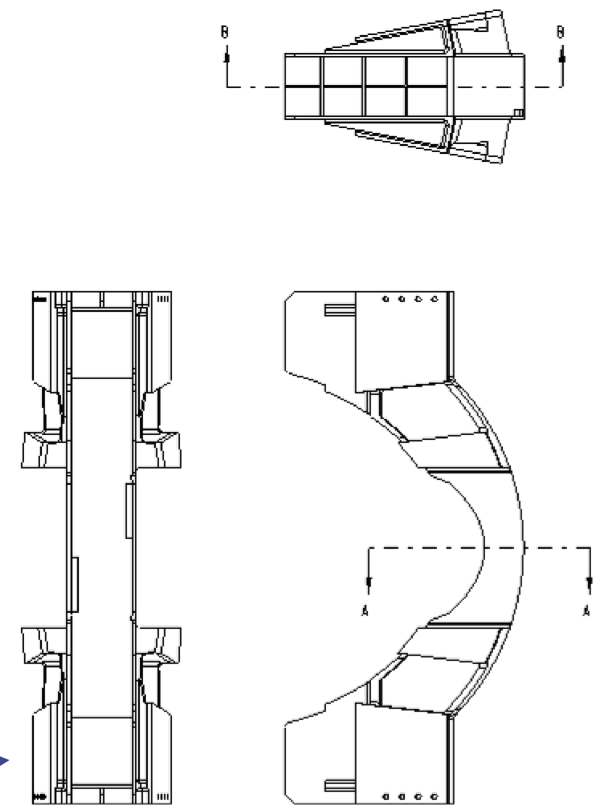
- 0.080” (2mm) Glass/epoxy or glass/polyimide sheet turn to turn;
- 0.034” (Glass/epoxy edge cuffs;
- 0.080” (2mm) glass/epoxy ground insulation;
- 0.360” (9mm) glass/epoxy potting compound



TF Coil Cases

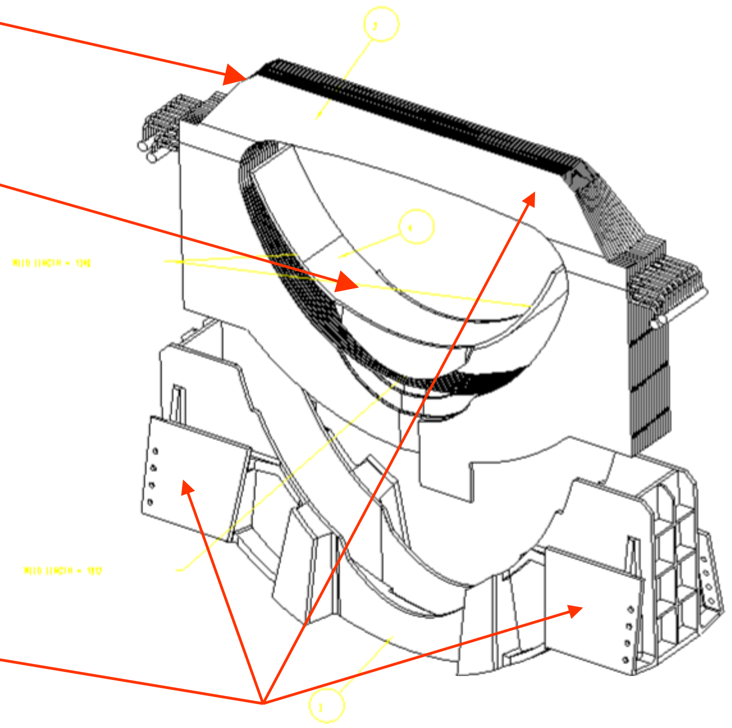
- Coil cases will be fabricated of 316-LN stainless steel.
- Case side and back plates will be pre-welded into an assembly.
- Case "wings" will be cast.
- G-10 interface plates will be machined for proper wedge fit-up of coils at assembly.



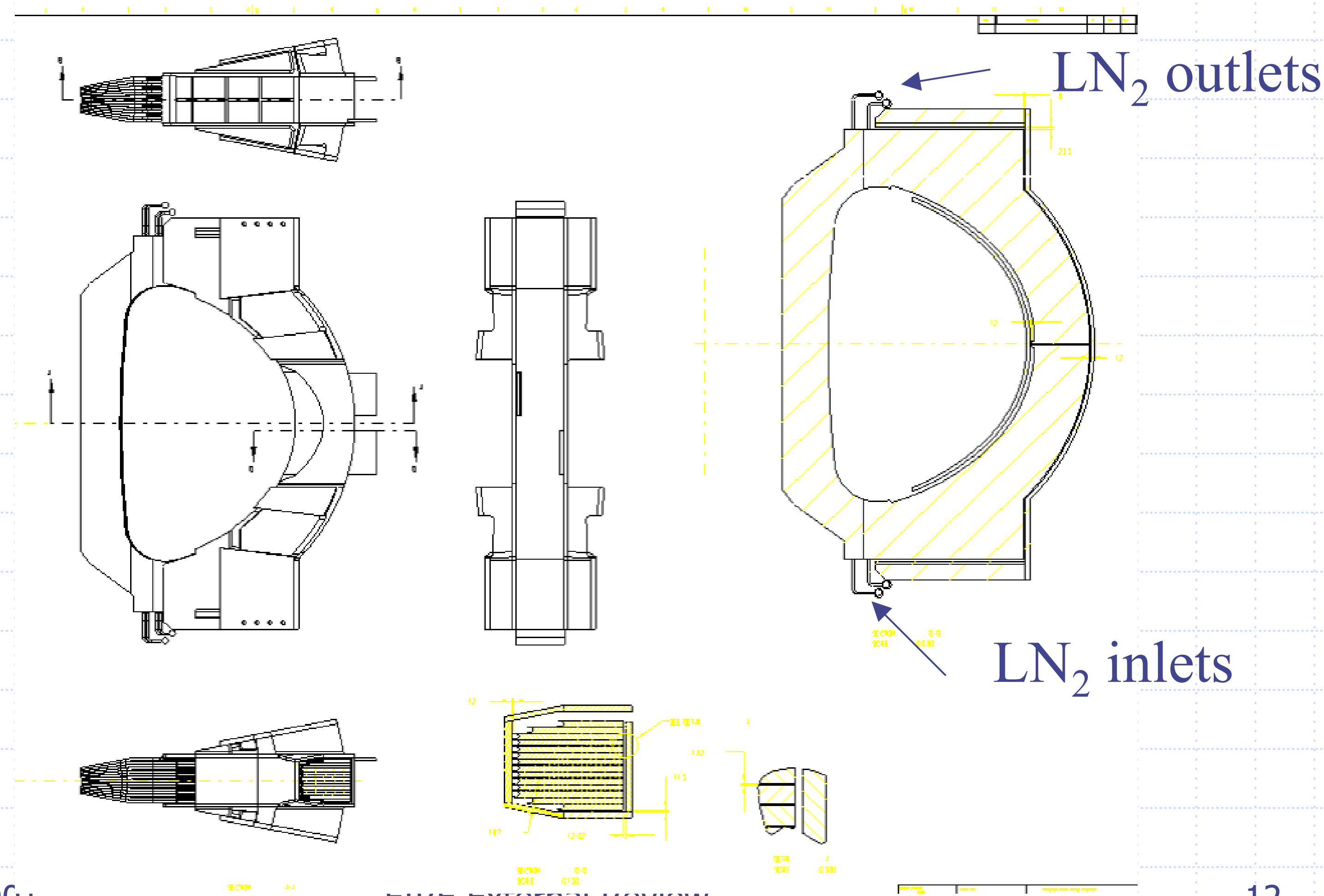


Installation of Winding into Case

- Winding will be lowered into case and aligned.
- Inner wall section will be welded to complete the coil case.
- The coil will be potted into the case with epoxy.
- G-10 interface plates and coil wedging surfaces will be machined to ensure proper wedge fit-up of coils.



TF Coil Assembly Details



TF Coil Cost Estimates

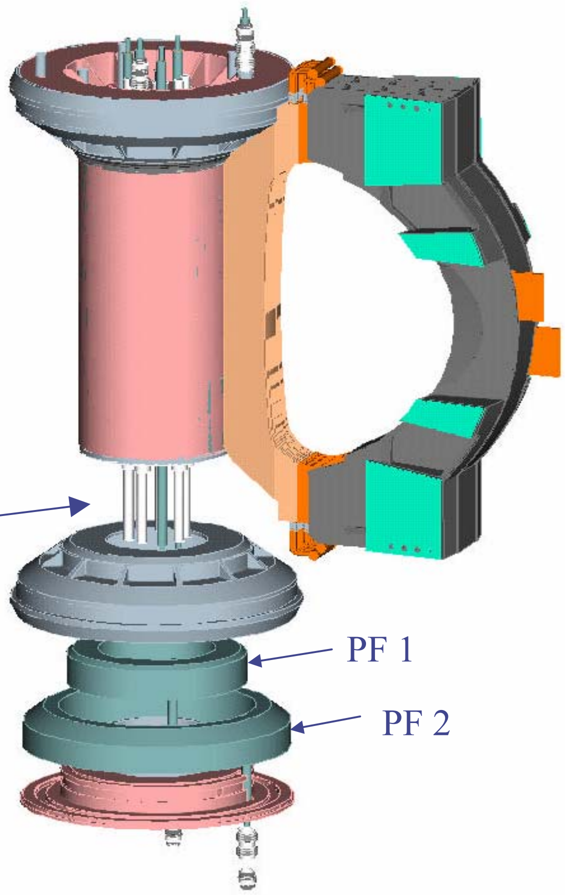
Item	Cost -M	Contingency-M	Total-M
TF Winding Packs	$91.30	$31.03	$122.33
TF cases and structure	$5.50	$1.70	$7.20
Assmbly of coils and cases	$2.40	$0.73	$3.13
TF power & cryo. Interfaces	$1.80	$0.37	$2.17
Engrg. & Design	$13.60	$3.40	$17.00
			$151.83

Weight per coil (winding + case): 43.3 tonnes (95260 lbs.)

Cost per coil: $9.5M; **$/lb.: 99.61** ($219.15/kg)

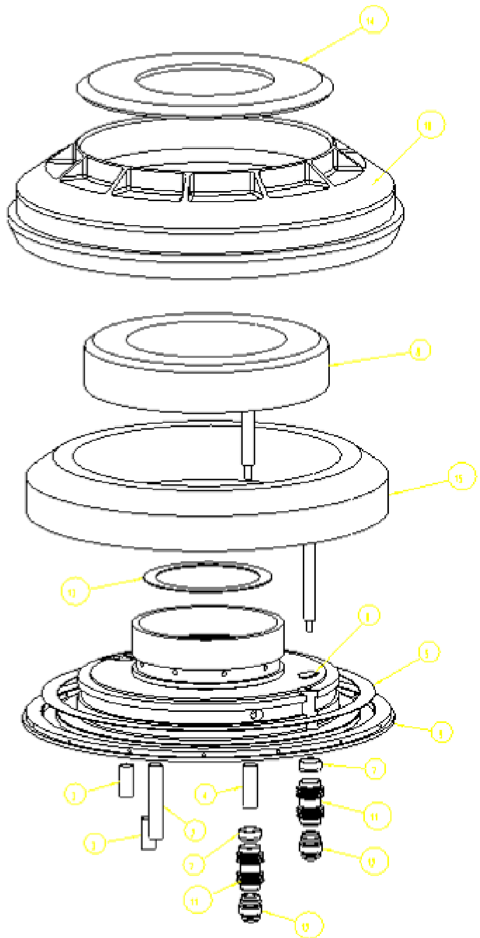
Assembly of the CS with the PF 1-2 Coil Castings

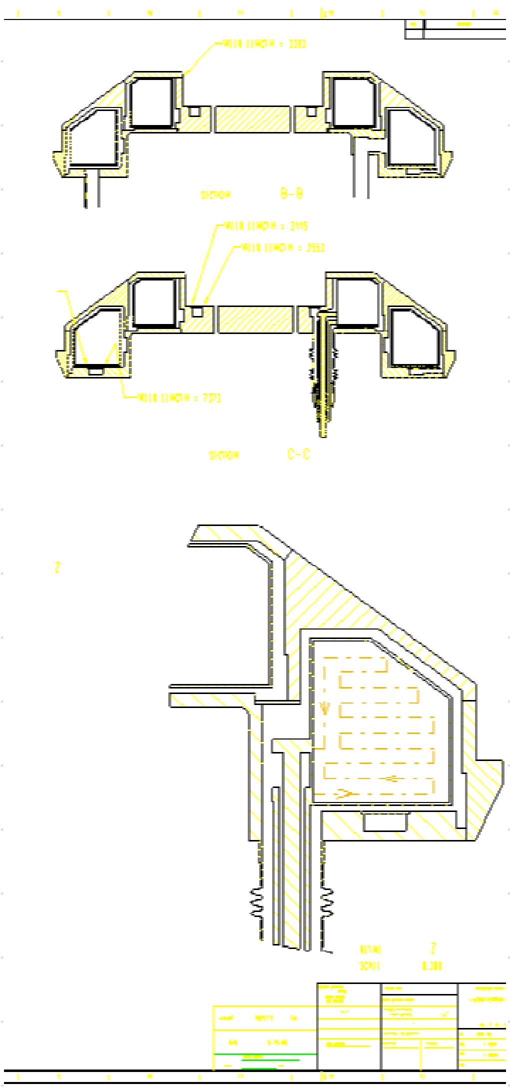
- Casting contains the PF 1&2 coils.
  - Similar lower PF casting assembly.
- Tie rods connect the two castings to the central solenoid and maintain preload on the CS coils.



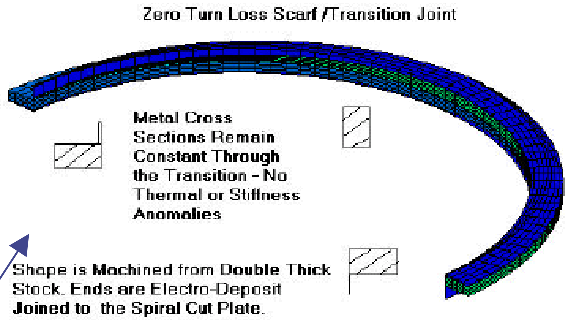
PF Casting Assembly

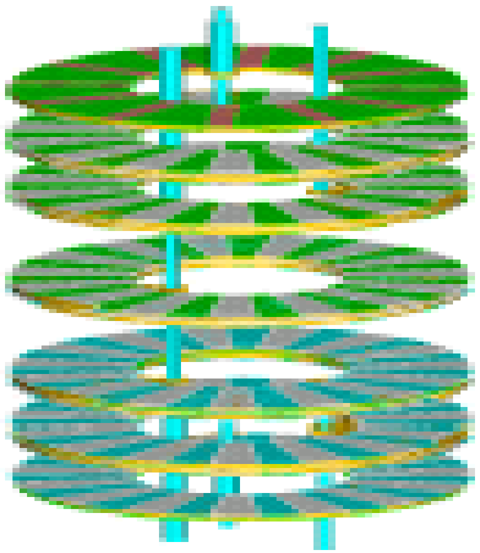
- PF 1&2 are located in castings which attach to the ends of the central solenoid.





Central Solenoid and PF 1&2 Manufacturing Details

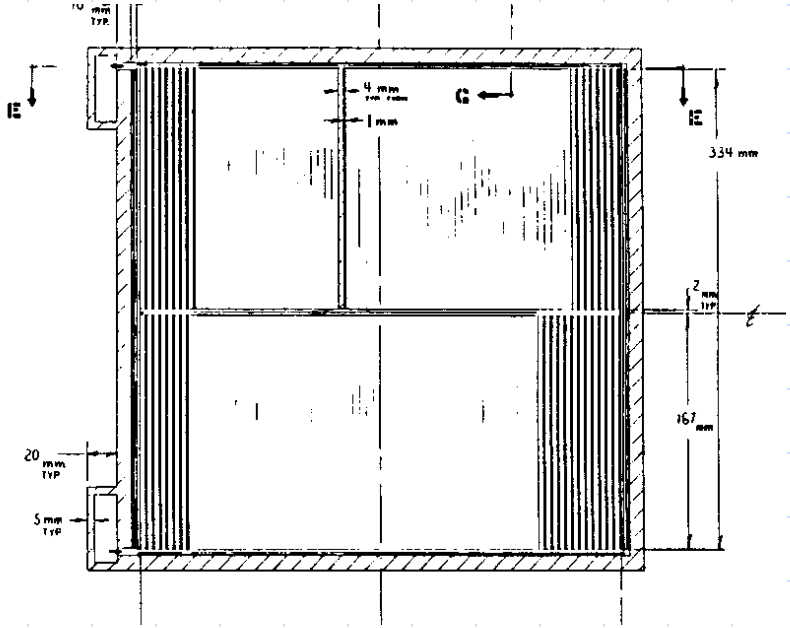




- Windings are water jet cut from forged C10200 copper discs.
- Specially shaped layer to layer transition pieces are joined by electroform welding.
- Winding is "sprung apart" to insulate the individual turns. A T-T insulation spacer strip is installed.
- G-10 insulating plates have radial grooves ; LN_2 flows from ID to OD to cool the turns.

Ring Coil Design – PF 3 and 4, upper and lower

- A strip wound copper design similar to that proposed for BPX is used for FIRE's ring coils.
- Winding is encased to direct LN_2 around coil perimeter for cooling.

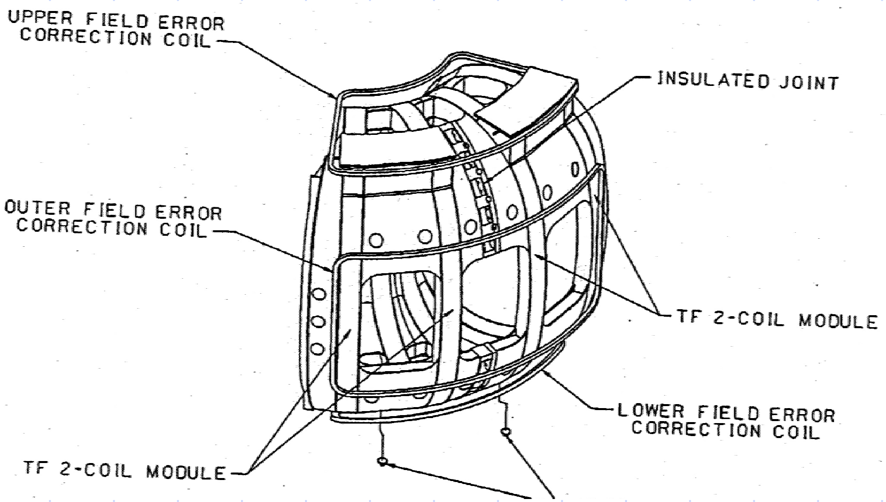


PF Coil Cost Estimates

Coil No.	R(m)	N(turns)	I (kA)	NI (kA-T)	Weight-kG			
CS1U	0.61	200	64.3	12860	19000			
CS1L	0.61	200	64.3	12860	19000			
CS2U	0.61	100	73.7	7370	11000			
CS2L	0.61	100	73.7	7370	11000		Solenoid Assembly	
CS3U	0.61	100	73.7	7370	11000		$6.6M+$2.2M cont.=	
CS3L	0.61	100	73.7	7370	11000		**$8.8M**	
PF1U	0.8	80	57	4560	10000			
PF1L	0.8	80	57	4560	10000		$/kg=	$66.67
PF2U	1.2	80	57	4560	15000		$/lb. =	$30.30
PF2L	1.2	80	57	4560	15000			
				Total:	**132000**	kG		
							Ring coils	
PF3U	3.7	60	53.2	3192	31000		$12.3 M+$2.7M=	
PF3L	3.7	60	53.2	3192	31000		**$15.0M**	
PF4U	3.7	60	53.2	3192	31000			
PF4L	3.7	60	53.2	3192	31000		$/kg=	$120.97
				Total:	**124000**	kG	$/lb. =	$54.99
Costs include structures/cases.								

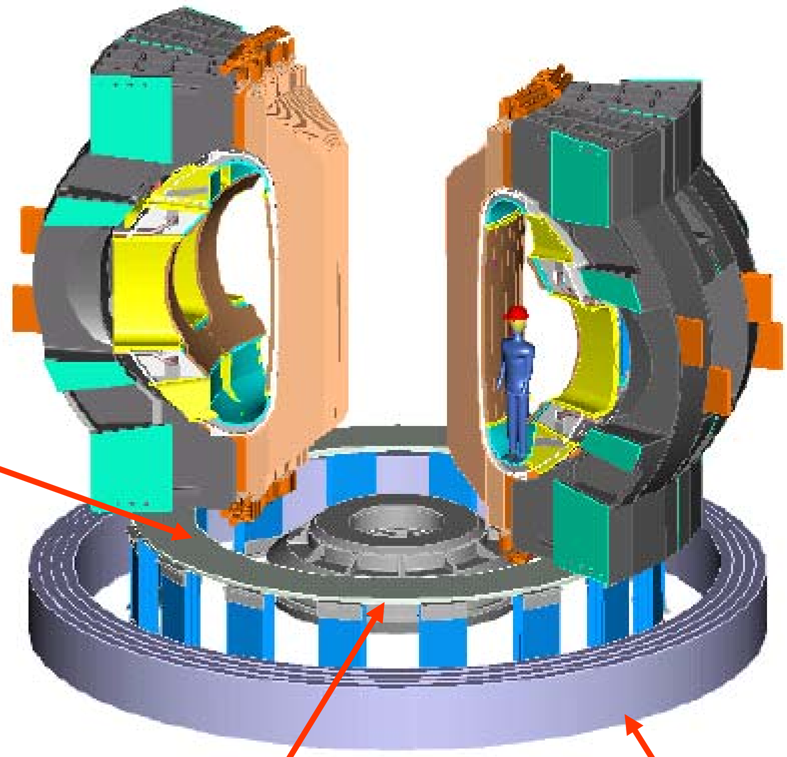
Note: Weights are for winding only. Ring coils currently have a “placeholder” of $5M for coil cases which are included above.

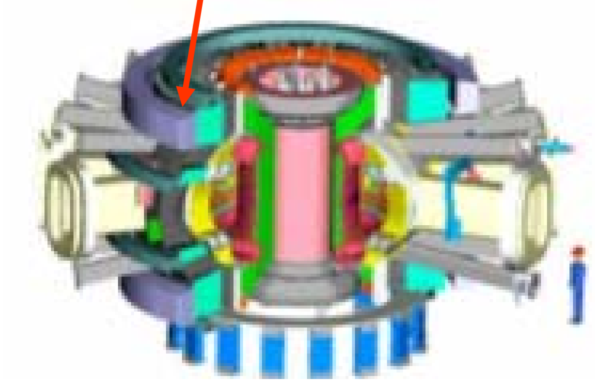
Field Error Correction Coils



- The field error correction coils consist of 12 “picture frame” type coils.
- Requirements have not yet been developed; costs scaled from TPX: $1.8M + 0.3M contingency

FIRE Structure





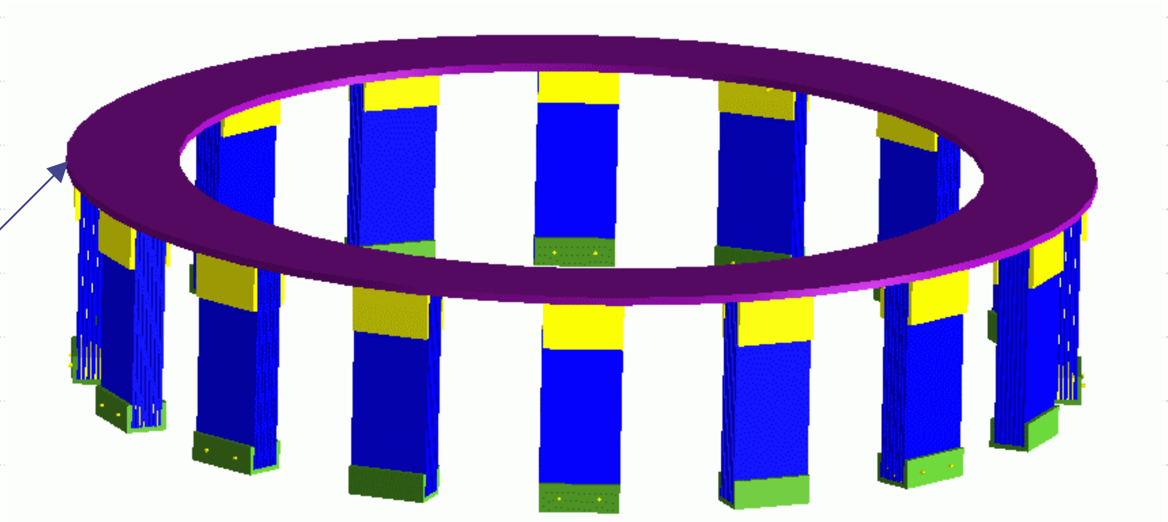
1&2. TF Support Ring and Gravity Supports

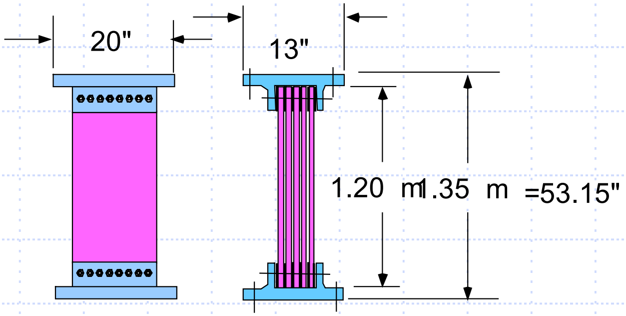
Cost Estimate: Ring + supports

$0.53M + 0.1 M contingency

$19.69/lb. ($43.32/kg)

Ring: ~13,000 lbs.



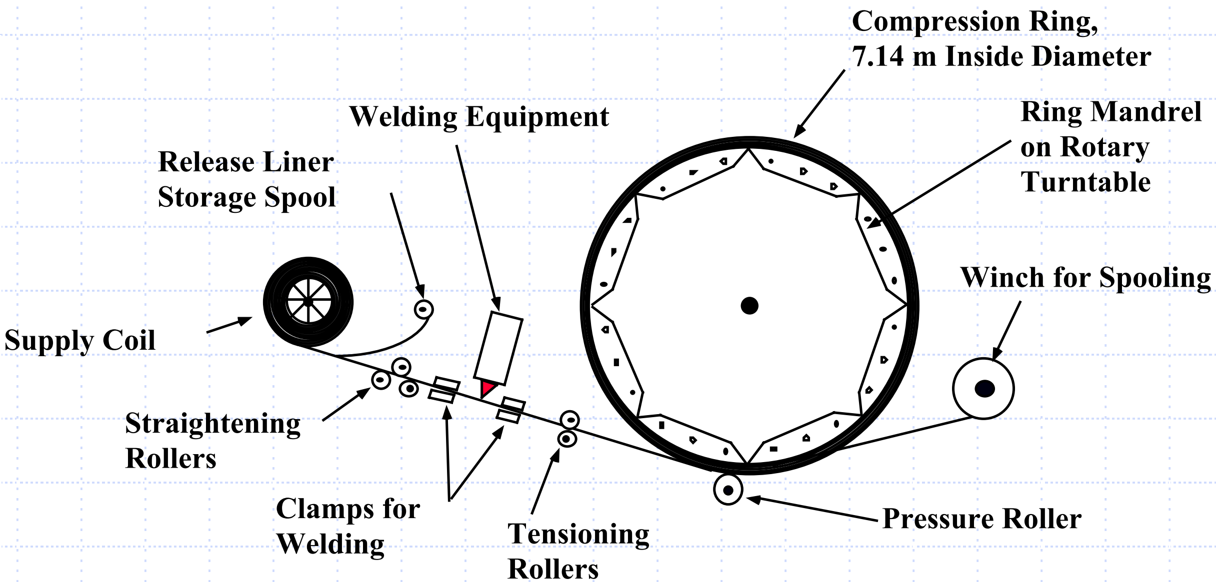


Gravity supports: ~20,000 lbs.

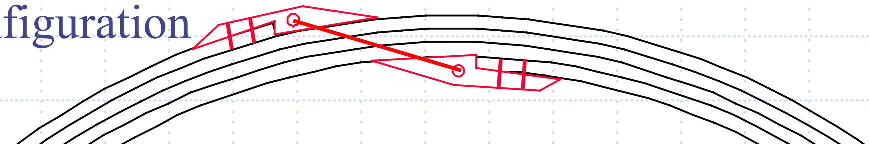
The sixteen flex supports consist of five support plates 2 cm thick by 50 cm wide by 120 cm long separated by 1 cm spacers.

3. Laminated Compression Rings

- Will be wound on site
- Interturn insulation to minimize induced currents.
- Weight for 2 rings: ~461,000 lbs.



Possible end tie configuration



Cost estimate: $5.7M + $1.1M contingency for 2 rings

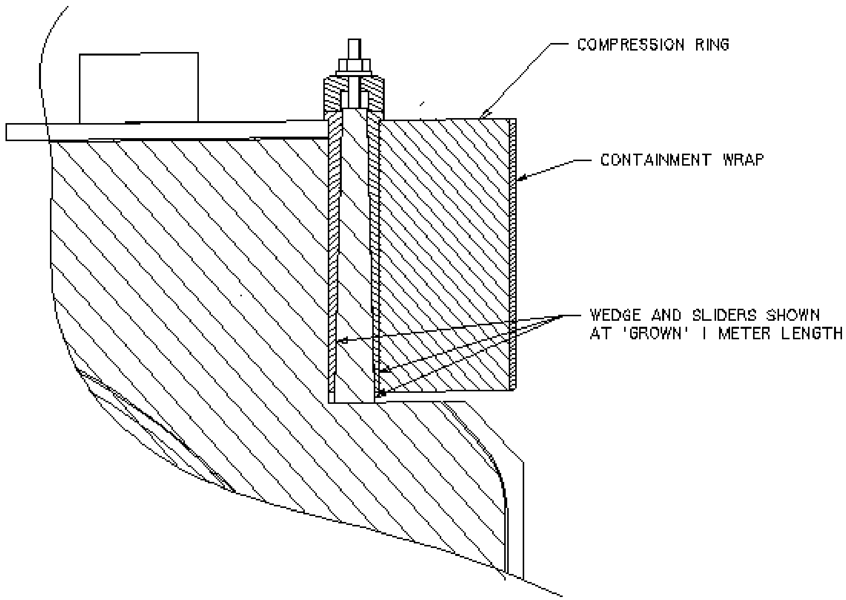
$14.75/lb. ($32.45/kg)

4. Radial Compression Mechanisms

Cost estimate: $2.4M + 0.48M contingency

(Weight for 16 mechanisms: ~173,000 lbs.)

$16.65/lb. ($36.63/kg)



Summary

- FIRE's cost estimates were developed using preliminary specifications to guide the process.
  - TF, PF coils, and structure were estimated by industry, using a combination of budgetary estimates from suppliers and internal estimates.
  - Field error coil costs were scaled from TPX.
- FIRE uses a plate type TF design similar to BPX. C17510 BeCu inner legs; C10200 for the remainder. Est. cost: $99.61/lb. ($219.15/kg)
- FIRE's CS coils are made from water jet cut forged C10200 copper discs. Layers connected by a "zero turn loss" transition piece joined by electroform welding. Machined G-10 plates permit radial flow of LN_2. Est. cost: $66.67/kg ($30.30/lb.)
- The ring coils are edge cooled C10200 strip wound coils. Est. cost: $120.97/kg ($54.99/lb.)
- Structures include a TF support ring, gravity supports and laminated radial compression rings and preload mechanisms. Estimated costs are in the range of $14.75-19.69/lb.

R&D Overview for FIRE's TF and PF Coils

P. Heitzenroeder and R. Thome
for the FIRE Team

Introduction

- FIRE has relatively modest R&D requirements since it is a cryo-cooled copper magnet tokamak and can draw upon a great deal of existing data from CIT/BPX, ALCATOR C-Mod, IGNITOR, and other high field, copper magnet tokamaks.

- **Planned R&D concentrates on items which permits higher performance, higher reliability, and helps to keep costs as low as possible.**

Planned Areas of R&D

1. Copper conductor characterization and design criteria
2. Copper conductor joint development
3. Radiation resistant insulating materials
4. Characterization of low friction insulating materials (a) for interfaces between CS coils; and (b) for the interface between the CS coils and TF coil in the Bucked and Wedged Design.
5. Characterization of high friction insulating materials for the inner legs of the TF coils.
6. Development & testing of the compression ring preload mechanism.

1. Copper Conductor and Design Criteria

Background:

- The data base requires assessment and extension for plates of the size to be procured for the full scale TF and PF conductor. The properties assumed requires validation.

Inner Leg of the Wedged TF baseline design-

- C17510 BeCu (68% IACS) in thick plate (36mm) form is used in the inner leg. The principal stresses are primarily axial tension and azimuthal compression. Required: UTS 800 MPa; min. yield: 724 MPa.

Wedged and Bucked and Wedged TF alternate design-

- Both designs use OFHC copper in thick plate form. This task will verify that the plate properties can be obtained in the thicknesses required.

Central Solenoid Coil: Both Wedged and Bucked and Wedged Alternate Design

- Both concepts use C10200 copper in thick plate (38mm) form. Rolled or forged copper discs are required to meet strength requirements. (350 MPa UTS; 300 MPa min. yield)

R&D Task:

- Obtain samples from full size plate stock and carry out a mechanical testing program to assure that static and crack growth properties at room and LN2 temperatures are adequate..

2. Conductor Joint Development

Background: Both the baseline and alternate TF coil designs require a high strength joining process which does not result in an annealed zone.

Baseline wedged design:

◈The baseline design uses C17510 BeCu for the inboard leg of the TF coils and C10200 copper for the balance of the coils. A cost effective, reliable high strength joining method for the material transition is essential.

Wedged and Bucked and wedged alternate design:

◈The bucked and wedged alternate TF design uses OFHC copper throughout the TF coil. In principal the turns for the latter could be cut from large thick plates, from which, the centers would be scrap. A cost effective joining method for joining plate segments would allow the TF legs to be fabricated from readily available plate sizes and eliminate the need to procure specially sized plates.

R&D Task:

◈Develop manufacturing processes and carry out a mechanical testing program to assure adequate mechanical properties and to validate design criteria for the joints. Potential candidate processes include friction stir welding and e-beam welding.

3. Radiation Resistant Insulating Materials

Background:

◆Data from the BPX insulation test program indicates that there are several glass/epoxy formulations (CTD-101; Shikazima) which can meet FIRE's requirement for radiation exposure capability of 1.5 x 10^{10} rads.

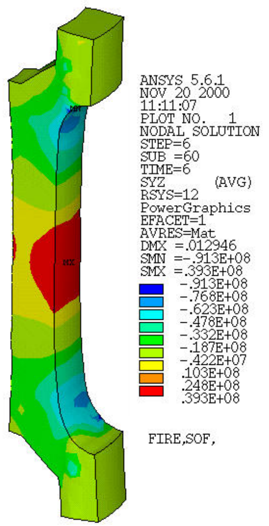
◆This is a high leverage R&D item, since it has the potential to permit more full power D-T shots and may permit the experimental program to be expanded with possibly only a minor impact on costs.

R&D Task:

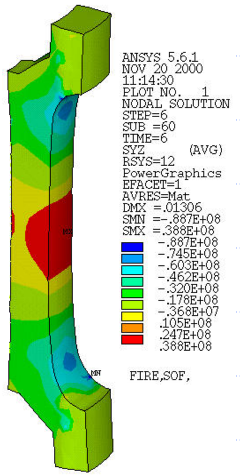
◆We plan to collaborate with several SBIRs which are underway to develop high radiation resistant insulating materials with good processing characteristics.

TF Inner Leg Insulation Frictional Requirements

Run #60 Mu=.3 at TF sides, SYZ Max=39.3



Run #61 Mu=.2 at TF sides, SYZ Max=38.8



TF Inner Leg Torsional Shear vs. TF Wedge Face Insulation Friction

(Run #60 Mu=.3 at TF sides, SYZ Max=39.3 Run #61 Mu=.2 at TF sides, SYZ Max=38.8)

- Torsional Shear Stress Distribution in the Inner Leg Indicates Amount of Slippage/Fretting
  - Continuous Axisymmetric Contours Indicates No Slippage; "Spots" Mid Build Indicate Bending Shear and some Slippage at the Wedge Surface

4a. Low Friction Insulation Characterization

Background: Criteria used in the design of the TF and CS coil systems require that selected interface areas retain a desired level of either low or high friction during operation.

Segmented Central Solenoid in both Wedged and Bucked & Wedged Designs-

- FIRE employs a segmented CS with a variation of currents among the 5 coils in the stack during a pulse.
  - Adjacent coils in the CS operate with different temperature and electromagnetic load profiles during a pulse.
  - Adjacent coils will strain differently and relative radial motion between coils in the CS will occur.
  - Interface must lock the coils azimuthally, maintain the coils co-axial, and allow relative radial motion with low friction.

R&D Tasks:

- Prototypes of the interface areas will be fabricated and tested under simulated operating conditions to verify operation and adequate life.

.

4b. Low Friction Insulating Material for the TF/CS Interface in Bucked Designs

- **Background:** The CS tends to expand radially and compress axially during operation. The inboard legs of the TF coils tend to stretch vertically due to their in-plane loads and shift azimuthally due to their out-of-plane loads. In a bucked design a low friction interface between the TF and CS is desirable to limit:
  - the CS vertical tension imposed by the TF,
  - transmission of torsional shear into the CS, and
  - radial-vertical traction shear imposed on the CS by the TF.

R&D Task:

- Select candidate materials and processes for application to the identified interfaces in the FIRE design.
- Apply low friction materials to substrates on a scale consistent with fabrication methods for FIRE.
- Perform mechanical tests to assure that expected surface friction performance is consistent with design criteria and reliable for the lifetime of the machine.
- Plans are to survey the significant work done in this area by CIT, IGNITOR, and ITER. We may only have to downselect from materials already identified.

5. High Friction Insulation Characterization

Background:

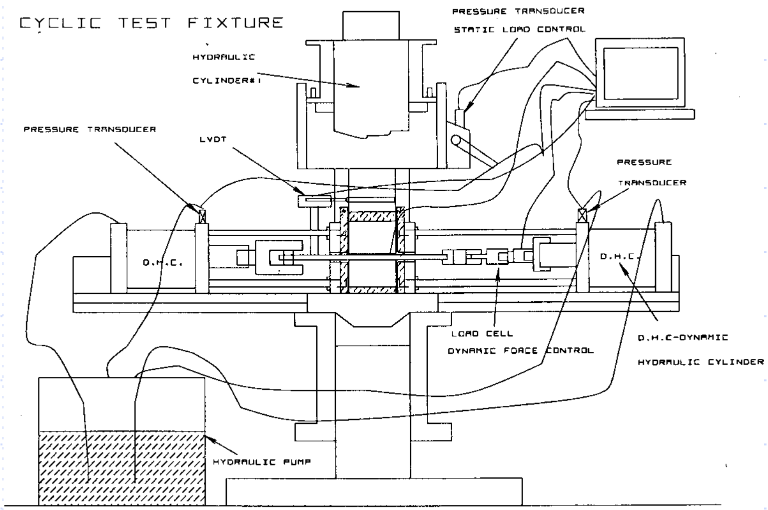
TF Coils in both Wedged and Bucked & Wedged Designs-

- Overturning moments on the TF coils are reacted by wedging action at the inboard legs and by shear between interfaces of the outer intercoil structures on the TF cases.
    - A friction coefficient of ~0.3 is needed between TF inboard legs to limit torsional motions and between cases on the outboard side to reduce shear pin and bolting requirements

R&D Task:

- Testing is required to verify friction coefficients and adequate life.

An Example of Available Low Friction Data



MEASURED STATIC FRICTION COEFFICIENT FOR SEVEN TYPES OF BEARING MATERIALS (1. FIBERSLIP B.40, 2. FIBERSLIP X1-40, 3. DU#1, 4. X-1200S, 5. FIBERGLIDE#6, 6. FIBRILOID, 7. LUBRITE HPF) WITH 36.7 ksi FACE COMPRESSION AT LN2

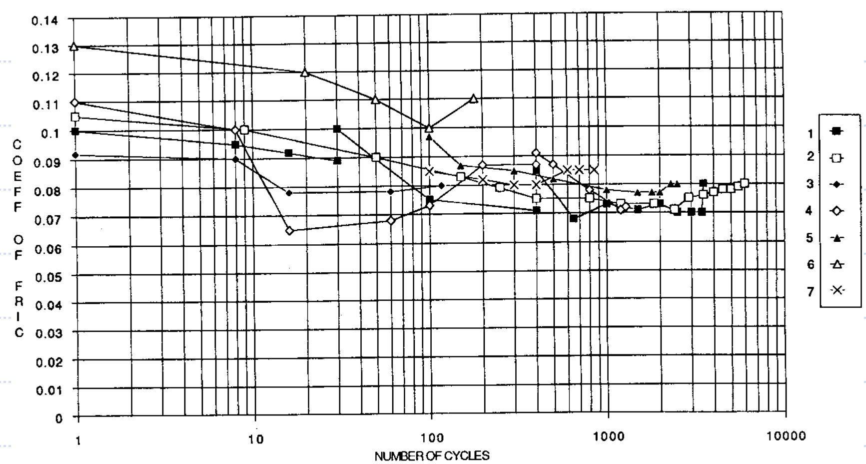
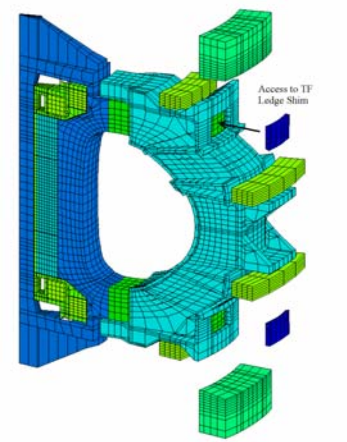


FIGURE 8

From: "Evaluation of Low Friction Materials for the Central Solenoid of the Compact Ignition Tokamak (CIT)" B.A.Smith, Z. Piek,P. Thomas, R Vieira MIT Plasma Fusion Center, Fusion Technology, Journal of the American Nuclear Society, Volume 19, Number 3,Part 2A, May 1991, page 1189



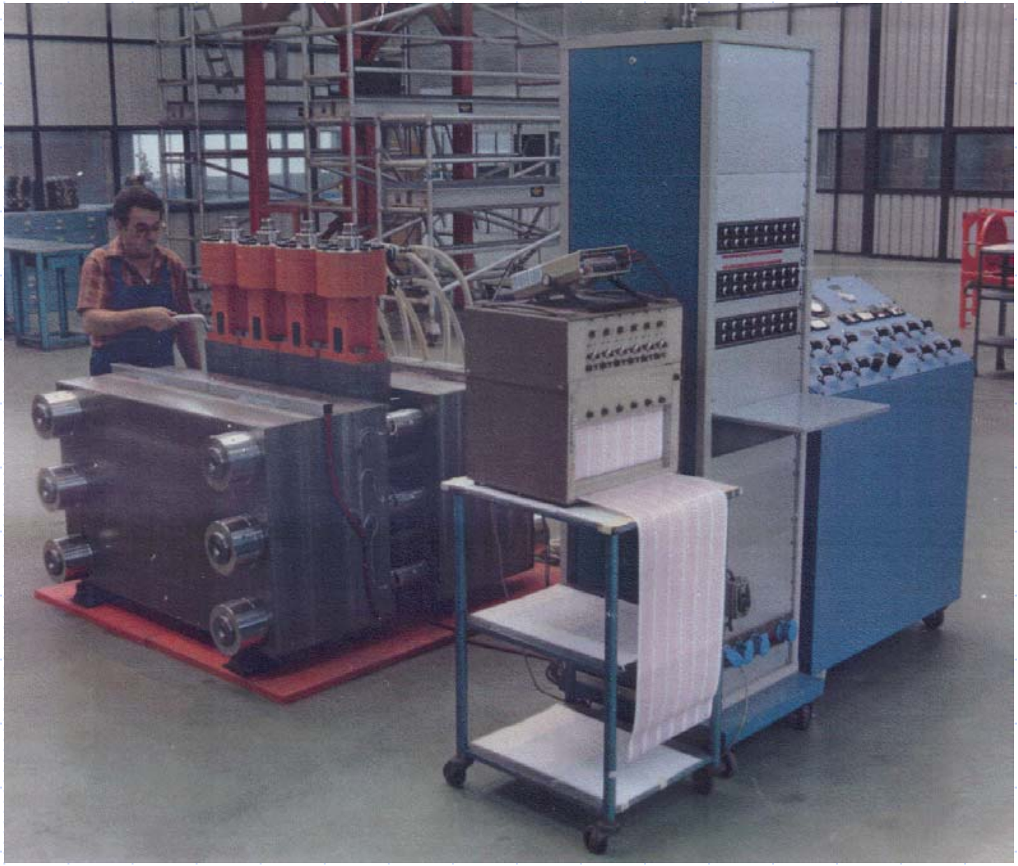
6. Ring Preload Jacking System

Background: Both the Wedged and the Bucked and Wedged TF coil designs use large steel rings outboard of the TF coils. The rings are pre-loaded at assembly using radial jacks to augment the wedge compression at the inboard faces of the TF coils and provide compression between the faces of the outboard intercoil structures during operation. The space available is very limited. Three jack concepts have been identified:

1. **A mechanical system (proposed for IGNITOR) consisting of opposing wedges**
2. **Stainless steel bladders with hydraulic fluid**
3. **Commercial "Enerpac" jacks**

R&D Task: Select one primary concept plus one back-up. Mock-up and test under expected operating conditions simulating assembly, cooldown, operational pressures, and temperatures.

IGNITOR Ring Preload Mechanism Design May Be Adoptable to FIRE



IGNITOR Preload Mechanism Being Tested