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**Westinghouse Electric Corporation
Fusion Power Systems Department**

**STRUCTURAL ANALYSIS
OF
TFTR TOROIDAL FIELD COIL
CONCEPTUAL DESIGN**

MASTER

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ABSTRACT

The conceptual design evaluation of the V-shaped toroidal field coils on the Tokamak Fusion Test Reactor has been performed by detailed structural analysis with the finite element method. The innovation provided by this design and verified in this work is the capability to support toroidal field loads while simultaneously performing the function of twist restraint against the device axial torques resulting from the vertical field loads.

The evaluations made for the conceptual design provide predictions for coil deflections and stresses. The results are available for the separate effects from toroidal fields, poloidal fields, and the thermal expansion of the coils as well as for the superposition of the primary loads and the primary plus thermal loads.

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1.0 INTRODUCTION

This report documents the structural evaluation methods and results for the conceptual design of the TFTR toroidal field coil assembly. The primary analysis effort was directed at demonstrating the feasibility of a TF coil design concept which provides total device axial torque resistance capability, thereby excluding the need for an external torque frame.

The finite element method of analysis was employed, and modeling was of sufficient detail to meet the objectives of: a) conducting parametric studies to include different design configurations, loading conditions, design tolerances and material property assumptions, b) calculating the TFTR device axial twist, axial growth and radial deformation with reasonable accuracy, and c) demonstrating any potentially high stressed location on the toroidal field coil that may require further detailed analyses - presumably with another, more detailed finite element model of the particular critical location.

The modeling assumptions that were used to evaluate the predicted range of machine axial twist included comparative results for: a) three different coil-to-coil bolt patterns, b) modeled material property variations resulting from tolerances on the copper epoxy winding and potting dimensions, c) shear panel pin tolerance, d) coil-to-coil interface bolt tolerance, e) coil-to-coil interface friction conditions, f) the load variations for different vertical field indices of curvature, and g) the loading conditions of an equilibrium field with and without a plasma.

The criteria from current Tokamak design practice for an acceptable TF coil rotation is approximately two milliradians. The analysis predictions for the conceptual design in this work, based upon the above modeling assumptions, range from about one to three milliradians of coil rotation about a device radial axis.

The toroidal field coil stresses were predicted for the separate and combined conditions of coil loads arising from the toroidal field, the equilibrium field with no plasma and the internal temperature differences between the copper windings and the stainless steel coil casing. A region of significantly high stress was identified on the coil stainless steel side wall, indicating a need for further analysis model refinements and/or some configuration modifications during preliminary design.

2.0 ANALYSIS METHOD

The analysis technique was the three-dimensional finite element method with the Reference (1), ANSYS computer code. The finite element models with displacement and load boundary conditions consistent with the assumed environmental field loads were generated with the computer programs PDXNODE, ELEMENT, and PDXFORC. These computer codes which provide significant automation for generating input data to finite element codes are best described in References (2) and (3). PDXNODE is a node point mesh generator developed for modeling the geometry of toroidal field coils. The program ELEMENT defines the finite elements of the model from the node points and from material property considerations. It simplifies the finite element input for coils whose geometric cross-sections are non-uniform, and it allows for a better approximation of material properties in coils that are anisotropic from the laminated layers of alternate epoxy and copper windings. The computer code PDXFORC was used to compute the three components of Lorentz force acting on every node point in the current-carrying portion of the finite element model. These forces are computed by the cross product of toroidal field current with the computed field from either the toroidal field coils or poloidal field coils. Additionally, PDXFORC is used to compute the loads on a TF coil when one or any number of the TF coils has experienced the faulted condition of short circuit.

The field load conditions that have been analyzed include toroidal field loads, the poloidal field loads from the EF coils with a 2.5 MA plasma current at a 2.48 meter machine radius, the poloidal field loads from the EF coils with no plasma, the toroidal field loads with a TF coil short circuit, and the combined toroidal and poloidal field loads. The descriptions to follow define the detailed geometric models with the related assumptions pertaining to material properties, loads, and boundary conditions.

2.1 MODEL GEOMETRIC REPRESENTATION

The finite element model was represented by a one-fourth geometric symmetric section of the V-shaped toroidal field coil defined on Figure 2.1-1 by the region occupied by one of the quadrants formed by the intersection of the machine horizontal midplane and the vertical midplane of a V-shaped TF coil. The differences between the model shown on Figure 2.1-1 and the Reference (4) conceptual design configuration are the bolt flange and shear panel simulations. The model has no flanges. The design flange is shown on Figures 2.1-3 and 2.1-4. The action of bolts on the model is transmitted to the coil at the single node points shown on Figure 2.1-1. The shear panels on the model conservatively contain less cross sectional area than the panels shown on the Reference (4) drawing. Also there is no direct model simulation for the panel pin connections shown on Figure 2.1-4. On the Figure 2.1-1 model, the panels are shown to tie directly to the coil side walls. The model was constructed of 45 layers of finite elements where each layer comprised a four degree segment of the coil circumference. The 46 layers of node points were generated using the Reference (2) computer program, PDXNODE. The computer run numbers*, (1) thru (4), define the node point geometry for Computations 21 and 21A. Run (5) is for 21B, and run (6) is for 21C. Computer run (7) defines the node point geometry for Computations 21D thru 21K. The 45 layers of finite elements were generated with the ELEMENT computer program as documented in Reference (2). Computer run (8) defines the finite element model for all the computations in the 21 series. Figure 2.1-1 shows the YZ plane view of the finite elements. Not detectable here is a layer of epoxy finite elements between the steel box and the copper windings. Figure 2.1-2 shows the finite element model section views AA thru DD defined on Figure 2.1-1. The total number of finite elements in the model is 2418 of the STIF-45 defined by Reference (1).

*For documentation purposes all the computer run output numbers are tabulated in Appendix A.

Figure 2.1-1. Analysis Model Geometry

Figure 2.1-2. Finite Element Description for Section Views Shown on Figure 2.1-1.

Figure 2.1-3. The TFTR Conceptual Design of the Toroidal Field Coil Interface View from Westinghouse Drawing No. 346838J.

2.2 MODEL BOUNDARY CONDITIONS

A one quarter geometric symmetric section of the toroidal field coil shown on Figure 2.1-1 was modeled for analyzing the structural effects from toroidal and poloidal magnetic fields and the coil internal temperature differences. The computed values of loads for the different field conditions are presented in Section 2.4 of this report.

2.2.1 Boundary Conditions for Poloidal Field Loading

The finite element model boundary conditions were the applied node point forces and the imposed node point displacements. The node point forces were applied in the copper regions of the model where the poloidal field crosses the TF coil current. The node point displacement conditions imposed to permit a one-fourth geometric symmetric model evaluation were the following: (a) the node points at the horizontal midplane ($Z = 0$) of the coil can displace in the Z -direction only, (b) the node points at the coil vertical midplane ($X' = 0$) can displace in the X' -direction only, and (c) the node points at the coil-to-coil vertical interface ($X = 0$) that simulated the bolt locations can displace in the X -direction only with exception to any bolt fit tolerances in the Y or Z directions.

2.2.2 Boundary Conditions for Toroidal Field Loading

The model boundary conditions for toroidal field load analysis included the three components of force on every node point in the copper region of the model resulting from the cross product of the toroidal field and the TF coil current. The displacement constraints included no Z -direction motion for nodes at the $Z = 0$ plane, no X direction displacement for nodes at the $X = 0$ plane and no X' -direction displacement for node points on the $X' = 0$ plane.

2.2.3 Boundary Conditions for Thermal Loading

The thermal stress and deflection analysis for the toroidal field coil was modeled by subjecting the entire structure to a uniform temperature increase. The steel portion of the model

was conservatively given a fictiously low coefficient of thermal expansion to simulate virtually no temperature change in the steel, and the copper/epoxy portions of the model were given true values of expansion coefficients. The specified displacement boundary conditions were the same as those applied for the toroidal field load analysis. These were zero displacement in the direction normal to the planes for the nodes on the horizontal midplane ($Z = 0$) and the two vertical planes formed by the 9 degree wedge section of the one-fourth geometric symmetric section of a V-shaped toroidal field coil.

2.2.4 Boundary Conditions for Combined Toroidal and Poloidal Field Loading

The combined load stress analysis can be modeled in one of two ways. The first way is to algebraically add the stress components from the individual cases and then recompute the principal stresses and the maximum shear stress from the superposition of stresses. The other method is to apply the toroidal field node point loads simultaneously with some shear and displacement conditions computed at the horizontal ($Z = 0$) and vertical ($X' = 0$ and $X = 0$) boundary planes by the poloidal field load analysis model. This gives the combined stress in two of the four TF coil quadrants. The combined stress in the other two quadrants is obtained by applying the toroidal field node point loads simultaneously with the negative of (shear and displacement) conditions on the horizontal and vertical boundary planes by the poloidal field load analysis model.

The specific boundary conditions as computed by the poloidal field load analysis model are the following: (a) the node point deflections at the horizontal midplane in the direction normal to that plane, (b) the node point shears at the horizontal midplane in the directions tangent to that plane, (c) the node point deflections at the coil-to-coil vertical interface in a direction normal to that plane, (d) the bolt shear loads at the coil-to-coil vertical interface in the directions tangent to that plane, (e) the node point deflections at the vertical midplane of a single TF coil in a direction normal to that plane, (f) the node point shears at the vertical midplane of a single TF coil in the directions tangent to that plane, and (g) at the node points on the lines formed by the two vertical planes inter-

secting the horizontal midplane a shear load would not be applied in the same direction at which a displacement is specified.

2.3 MATERIAL PROPERTIES

The material property input data requirement for the finite element stress code includes the Young's Modulus (E), the Poisson Ratio (ν), the density (ρ), and the coefficient of thermal expansion (α). An optional input is the shear modulus (G) which may be necessary when it differs from the value of $E/2(1 + \nu)$. The property values for E, α , and ν in the three orthogonal directions of the model global rectangular cartesian coordinate system are required as input data. The material property input data for Armco 18-3 Mn Stainless Steel included:

$$\begin{aligned}E_X &= E_Y = E_Z = 28.8 \times 10^6 \text{ psi } (0.199 \times 10^6 \text{ MPa}) \\ \alpha_X &= \alpha_Y = \alpha_Z = 8.93 \times 10^{-6} \text{ in/in/}^\circ\text{F } (16.07 \times 10^{-6} \text{ mm/mm/}^\circ\text{C}) \\ \nu_{XY} &= \nu_{XZ} = \nu_{YZ} = 0.295 \\ \rho &= 0.280 \text{ lb/in}^3 \text{ } (7.755 \text{ g/cm}^3)\end{aligned}$$

The material property input data for the epoxy included:

$$\begin{aligned}E_X &= E_Y = E_Z = 0.55 \times 10^6 \text{ psi } (0.00379 \times 10^6 \text{ MPa}) \\ \alpha_X &= \alpha_Y = \alpha_Z = 4.0 \times 10^{-6} \text{ in/in/}^\circ\text{F } (7.2 \times 10^{-6} \text{ mm/mm/}^\circ\text{C}) \\ \nu_{XY} &= \nu_{XZ} = \nu_{YZ} = 0.30 \\ \rho &= 0.065 \text{ lb/in}^3 \text{ } (1.8 \text{ g/cm}^3)\end{aligned}$$

The epoxy Young's modulus was based on a calculation for the composite epoxy-copper wound PLT, TF coil so that the experimental PLT toroidal field coil deflections would agree with finite element model predictions. Normal published values of E for epoxy vary from 1 to 4 million psi. In addition to steel and epoxy, a third material was used to model the TF coil. This third material is a laminated composite of copper and epoxy windings.

The copper properties used in series and in parallel with the epoxy to define this anisotropic composite included for (copper, OFHC)

$$E = 17 \times 10^6 \text{ psi } (0.117 \times 10^6 \text{ MPa})$$

$$\alpha = 9 \times 10^{-6} \text{ in/in/}^\circ\text{F } (16.2 \times 10^{-6} \text{ mm/mm/}^\circ\text{C})$$

$$\nu = 0.3$$

$$\rho = 0.323 \text{ lb/in}^3 \text{ (} 8.92 \text{ g/cm}^3 \text{)}$$

The derivation of material properties for the anisotropic composite formed by alternate layers of copper and epoxy is first formulated in the local (R, θ , X) coordinate system of the TF coil and then these property values are transformed to the model global coordinate system as required for input to the finite element stress code. In the coil radial (R) direction, the copper and epoxy are assumed to be in series, and in the coil hoop (θ) and axial (X) directions, the materials are modeled as parallel springs. The coil material thicknesses in the radial direction assumed for Computation 21, where

$$L_c = 15.02 \text{ in. (total copper thickness) } (38.15 \text{ cm})$$

$$L_e = 1.84 \text{ in. (total epoxy between copper turns) } (4.67 \text{ cm})$$

This leaves space for an additional epoxy radial thickness of 0.2 in. (0.508 cm) adjacent to the steel containment radial surfaces which is modeled in the structure with the previously stated material properties for epoxy. The composite material properties in the coil local (R, θ , X) coordinate system are:

$$E_\theta = E_X = \frac{\sum E_i L_i}{\sum L_i} = \frac{17 (15.02) + 0.55 (1.84)}{15.02 + 1.84} = 15.2 \times 10^6 \text{ psi} \\ (0.104 \times 10^6 \text{ MPa})$$

$$E_R = \frac{\sum L_i}{\sum \frac{L_i}{E_i}} = \frac{15.02 + 1.84}{\frac{15.02}{17 \times 10^6} + \frac{1.84}{0.55 \times 10^6}} = 3.98 \times 10^6 \text{ psi} \quad (0.0274 \times 10^6 \text{ MPa})$$

$$G_{X\theta} = \frac{\sum G_i L_i}{\sum L_i} = \frac{1}{2(1+\nu)} \frac{\sum E_i L_i}{\sum L_i} = \frac{E_\theta}{2(1+\nu)} = \frac{15.2 \times 10^6}{2.6} = 5.85 \times 10^6 \text{ psi} \quad (0.0403 \times 10^6 \text{ MPa})$$

$$G_{XR} = G_{\theta R} = \frac{\sum L_i}{\sum \frac{L_i}{G_i}} = \frac{1}{2(1+\nu)} \frac{\sum L_i}{\sum \frac{L_i}{E_i}} = \frac{E_R}{2(1+\nu)} = \frac{3.98 \times 10^6}{2.6} = 1.53 \times 10^6 \text{ psi} \quad (0.0105 \times 10^6 \text{ MPa})$$

The global (X, Y, Z) coordinate system for the model is related to the coil local (R, θ , X) coordinate system as schematically shown where the X global is the same direction as X local.

The approximations to material stiffnesses in the global coordinate system for input data purposes follows:

$$F_Z = F_\theta \cos \theta + F_R \sin \theta$$

$$k_z \Delta Z = k_\theta \Delta \theta \cos \theta + k_r \Delta R \sin \theta$$

$$\Delta R = \Delta Z \sin \theta$$

$$\Delta \theta = \Delta Z \cos \theta$$

$$k_z = k_\theta \cos^2 \theta + k_r \sin^2 \theta = k_\theta + (k_r - k_\theta) \sin^2 \theta$$

or

$$E_Z = E_\theta + (E_R - E_\theta) \sin^2 \theta$$

Similarly,

$$E_Y = E_R + (E_\theta - E_R) \sin^2 \theta$$

$$G_{YZ} = G_R \theta$$

$$G_{XY} = \frac{1}{2} E_Y / (1 + \nu)$$

$$G_{XZ} = \frac{1}{2} E_Z / (1 + \nu)$$

The finite element model described in Section 2.1 shows 45 layers of elements from $\theta = 0$ to π . Material number one in the model is the steel portions of the structure, and material number two is the epoxy region between the windings and the steel case, and materials 3 thru 25 represent the composite of laminated copper and epoxy. Table 2.3-1 shows for Computation 21 the values of material modulus used to represent the composite material. It shows the model being approximated with 23 different materials.

For Computations 21A thru 21K the distribution of copper and epoxy within the steel box was assumed for the purpose of computing the Young's modulus and the shear modulus of the composite to be such that all of the non-copper would be located between turns as:

TABLE 2.3-1

YOUNG'S MODULUS AND SHEAR MODULUS USED IN COMPUTATION 21
TO MODEL THE LAMINATED COPPER AND EPOXY

Material Number	Angle θ , Degrees	$E_X \cdot 10^6$ psi	$E_Y \cdot 10^6$ psi	$E_Z \cdot 10^6$ psi	$G_{YZ} \cdot 10^6$ psi	$G_{XY} \cdot 10^6$ psi	$G_{XZ} \cdot 10^6$ psi
3	2 and 178	15.20	3.99	15.19	1.53	1.53	5.84
4	6 174		4.10	15.08		1.57	5.80
5	10 170		4.31	14.86		1.65	5.71
6	14 166		4.63	14.55		1.78	5.59
7	18 162		5.05	14.13		1.94	5.43
8	22 158		5.55	13.63		2.13	5.24
9	26 154		6.13	13.05		2.35	5.02
10	30 150		6.78	12.40		2.60	4.77
11	34 146		7.48	11.70		2.87	4.50
12	38 142		8.23	10.95		3.16	4.21
13	42 138		9.00	10.18		3.46	3.91
14	46 134		9.78	9.40		3.76	3.61
15	50 130		10.56	8.62		4.06	3.31
16	54 126		11.32	7.86		4.35	3.02
17	58 122		12.04	7.13		4.63	2.74
18	62 118		12.72	6.46		4.89	2.48
19	66 114		13.34	5.84		5.13	2.24
20	70 110		13.88	5.30		5.33	2.03
21	74 106		14.34	4.84		5.51	1.86
22	78 102		14.71	4.47		5.65	1.72
23	82 98		14.98	4.20		5.76	1.61
24	86 94		15.14	4.04		5.82	1.55
25	90		15.20	3.98		5.84	1.53

$$L_c = 15.00 \text{ (total copper thickness) (38.1 cm)}$$

$$L_e = 17.26 - 15.00 = 2.26 \text{ (total epoxy thickness) (5.74 cm)}$$

For these material proportions, the composite properties are:

$$E_\theta = E_X = 14.85 \times 10^6 \text{ psi (0.102} \times 10^6 \text{ MPa)}$$

$$E_R = 3.46 \times 10^6 \text{ psi (0.0238} \times 10^6 \text{ MPa)}$$

$$G_{YZ} = 1.33 \times 10^6 \text{ psi (0.0091} \times 10^6 \text{ MPa)}$$

This is a conservatively more flexible composition of material than that used for Computation 21, because in both models there is still maintained a filler of epoxy material between the steel structure and the copper windings. Table 2.3-2 shows the transformed values of these properties to the model global coordinate system.

The derivation of material properties for an approximation of the model thermal expansion (Computation 21J) is the following. The analysis model (21J) assumed that the copper windings undergo a uniform temperature change, but the steel portion of the structure does not experience a temperature rise. To simulate this, the entire finite element model was subjected to a uniform temperature change. But in doing so, the steel portion of the structure was given a thermal expansion coefficient of one-thousandth of its true value.

$$\alpha_{\text{steel}} = 8.93 \times 10^{-9} \text{ in/in/}^\circ\text{F (16.07} \times 10^{-9} \text{ mm/mm/}^\circ\text{C)}$$

In the copper/epoxy composite region of the model, the expansion coefficients were modeled as the following where the subscripts are copper (c) and epoxy(e):

TABLE 2.3-2

YOUNG'S MODULUS AND SHEAR MODULUS USED IN COMPUTATIONS 21A
THROUGH 21K TO MODEL THE LAMINATED COPPER AND EPOXY

Material Number	Angle θ , Degrees	$E_X \cdot 10^6$ psi	$E_Y \cdot 10^6$ psi	$E_Z \cdot 10^6$ psi	$G_{YZ} \cdot 10^6$ psi	$G_{XY} \cdot 10^6$ psi	$G_{XZ} \cdot 10^6$ psi
3	2 and 178	14.85	3.47	14.84	1.33	1.33	5.71
4	6 174		3.58	14.73		1.38	5.67
5	10 170		3.80	14.51		1.46	5.58
6	14 166		4.13	14.18		1.59	5.45
7	18 162		4.55	13.76		1.75	5.29
8	22 158		5.06	13.25		1.95	5.10
9	26 154		5.65	12.66		2.17	4.87
10	30 150		6.31	12.00		2.43	4.62
11	34 146		7.02	11.29		2.70	4.34
12	38 142		7.78	10.53		2.99	4.05
13	42 138		8.56	9.75		3.29	3.75
14	46 134		9.35	8.96		3.60	3.45
15	50 130		10.14	8.17		3.90	3.14
16	54 126		10.91	7.40		4.20	2.85
17	58 122		11.65	6.66		4.48	2.56
18	62 118		12.34	5.97		4.75	2.30
19	66 114		12.97	5.34		4.99	2.05
20	70 110		13.52	4.79		5.20	1.84
21	74 106		13.98	4.33		5.38	1.67
22	78 102		14.36	3.95		5.52	1.52
23	82 98		14.63	3.68		5.63	1.42
24	86 94		14.79	3.52		5.69	1.35
25	90		14.85	3.46		5.71	1.33

Coil Radial Direction

$$\alpha_R = \frac{\alpha_e L_e + \alpha_c L_c}{L_e + L_c} = \frac{9(15) + 4(1.89)}{16.89} = 8.44 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$
$$= (15.19 \times 10^{-6} \text{ m/m/}^\circ\text{C})$$

Coil Hoop and Axial Direction

$$\alpha_\theta = \alpha_X = \alpha_e + \frac{\alpha_c + \alpha_e}{\left(1 + \frac{E_e L_e}{E_c L_c}\right)}$$
$$= 4 \times 10^{-6} + \frac{(9 - 4) \times 10^{-6}}{\left(1 + \frac{0.55(1.89)}{17(15)}\right)} = 8.98 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$
$$= (16.16 \times 10^{-6} \text{ mm/mm/}^\circ\text{C})$$

The transformations from the coil local coordinates to the model global coordinates follows.

$$\alpha_X = \alpha_X$$

$$\alpha_Y = \alpha_R + \sin^2 \theta (\alpha_\theta - \alpha_R)$$

$$\alpha_Z = \alpha_\theta + \sin^2 \theta (\alpha_R - \alpha_\theta)$$

Table 2.2-3 shows the transformed values of these properties for input to the finite element model for materials 3 thru 25.

TABLE 2.3-3

COEFFICIENTS OF THERMAL EXPANSION USED IN COMPUTATION 21J
TO MODEL THE LAMINATED COPPER AND EPOXY

Material Number	Angle θ , Degrees	$\alpha_X \cdot 10^{-6}$ in/in/°F	$\alpha_Y \cdot 10^{-6}$ in/in/°F	$\alpha_Z \cdot 10^{-6}$ in/in/°F
3	2 and 178	8.44	8.440	8.980
4	6 174		8.445	8.975
5	10 170		8.456	8.964
6	14 166		8.471	8.949
7	18 162		8.491	8.929
8	22 158		8.515	8.905
9	26 154		8.544	8.876
10	30 150		8.575	8.845
11	34 146		8.608	8.812
12	38 142		8.644	8.776
13	42 138		8.681	8.739
14	46 134		8.719	8.701
15	50 130		8.756	8.664
16	54 126		8.793	8.627
17	58 122		8.828	8.592
18	62 118		8.861	8.559
19	66 114		8.890	8.530
20	70 110		8.916	8.504
21	74 106		8.938	8.482
22	78 102		8.956	8.464
23	82 98		8.969	8.451
24	86 94		8.977	8.443
25	90		8.980	8.440

2.4 MODEL LOADS

This section of the report provides the specific values for the calculated loads that were applied as boundary conditions to the structural analysis models. The toroidal field coil loads have been evaluated as the vector cross product of TF coil current and the magnetic fields. The computer program that has been exclusively used for this purpose is PDXFORC as documented in Reference (3). The parameters, common to all of the field and load analysis include a device composed of 20 toroidal field coils each with a total of 3,200,800 amp turns. The coils are centered on a major machine radius of 2.8 m. The copper portion of a coil occupies the region bounded by ID = 2.912 m, OD = 3.768 m, and 0.1842 m is the pancake thickness of the coil copper halves in each side of the V-shape toroidal field coil.

2.4.1 Toroidal Field Loads

When the toroidal field crosses the TF coil current, the adjacent copper regions are mutually attracted, the copper is loaded toward the device center-line and the coils are tensioned in an axial direction away from the machine horizontal midplane. The total mutual attraction at each of the coil interfaces is a compression of (3,011,520 lb) 13.40 MN. The total centering force of each V-section is $(5,882,768 * \cos 9^\circ \text{ lb})$ 25.84 MN, and this results in 83.0 MN of normal compressive force at each of the coil interfaces from the wedge action. The axial direction tension in each of the V-sections is (6,037,792 lb) 26.86 MN. The distribution with respect to coil angular position of these loads from computer run (9) are provided on Figures 2.4-1 thru 2.4-3. The Lorentz force distributions from the toroidal field are shown by the curves labeled as "normal". Also shown on these curves are some load distributions for fault conditions.

2.4.2 Toroidal Field Fault Loads

The toroidal field loads on each of the toroidal field coils has been evaluated for the condition of a single TF coil short circuit and for half of the coils on the device to be in a short

Figure 2.4-1. Distributions of Toroidal Field Loads on TF Coil in the Machine Toroidal Direction

Figure 2.4-2. Distributions of Toroidal Field Loads on TF Coil in the Machine Radial Direction

Total Force (lb)	Condition
FZ (1a) = 3,018,896	Normal
FZ (1b) = 3,018,896	Normal
FZ (1a) = 2,559,152	Coil 20 Short
FZ (1b) = 2,640,582	Coil 20 Short
FZ (1a) = 1,787,652	Coils 11 to 20 Short
FZ (1b) = 1,958,224	Coils 11 to 20 Short
FZ (1a) = 2,994,874	Coil 11 Short
FZ (1b) = 2,994,874	Coil 11 Short

(See Figure 2.4-4 for Coil
Numbering and Notations)

One TF Coil:
Amp-Turns (a + b) = 3,200,800

Figure 2.4-3. Distributions of Toroidal Field Loads on TF Coil in the Machine Axial Direction

circuit. Figure 2.4-1 thru 2.4-3 show the distribution of these loads on coil number one when coil 20 is shorted and when coils 11 thru 20 are shorted. Table 2.4-1 provides the loads on any coil when any other coil is shorted. This table is used in conjunction with Figure 2.4-4. The computer run numbers for these faulted loads are (10) through (31).

2.4.3 Poloidal Field Loads

The poloidal field loads have been evaluated for two basic conditions. These are the equilibrium field with and without a plasma field crossing the TF coil current. These loads are of the direction which creates a machine twist about the machine centerline which is created by a moment produced on each TF coil about an axis formed by the intersection of the machine horizontal midplane and the vertical midplane of the TF coil. Table 2.4-2 defines a set of equilibrium field coils and the plasma by location and amp-turns. This combination produced the field that provided the TF coil loads for computations 21, 21A, 21B and 21C. Table 2.4-3 defines a later design for the equilibrium field coils (the hybrid, H7 configuration) which can provide three different indices of curvature. The coils 1 to 20 are EF, 21 to 34 are hybrid and coils 35 to 44 are referred to as curvature coils. This coil configuration was used for computations 21D, 21E, 21F and 21G. A trade study was performed to compare the loads for different indices of curvature and for the conditions with and without a plasma current. The results are presented in Table 2.4-4. The computer run numbers for these load calculations are (32) to (38).

2.4.4 Thermal Loads

The toroidal field coil copper windings are basically encased by a steel box. The copper portions of the coil, on the average, experience a larger temperature increase than the steel portion of the structure. The tendency for the copper expansion to be impeded by the cooler steel basically creates compression in the copper windings and tension in the steel support structure. For the purpose of making a preliminary estimate of these loads, it was assumed that on the average the copper is 60°F (33°C) hotter than the steel.

TABLE 2.4-1

TOROIDAL FIELD COIL FAULT LOADS

Figure 2.4-4 Notation	Coil Number One Shorted		
	Toroidal Field Force		
	Half Coil	Z-Dir. Force (lb)	Y-Dir. Force (lb)
1a	0	0	0
1b	0	0	0
2a	2,559,152	-2,402,380	-6,210,616
2b	2,640,582	-2,629,856	725,212
3a	2,752,257	-2,561,570	-4,134,516
3b	2,792,451	-2,685,382	2,120,872
4a	2,854,418	-2,684,286	-3,491,310
4b	2,876,387	-2,754,938	2,605,868
5a	2,913,713	-2,768,854	-3,235,418
5b	2,925,940	-2,809,382	2,810,972
6a	2,948,677	-2,823,128	-3,121,700
6b	2,955,565	-2,846,544	2,906,406
7a	2,969,566	-2,857,126	-3,067,458
7b	2,973,484	-2,870,748	2,953,912
8a	2,982,121	-2,878,170	-3,039,928
8b	2,984,340	-2,886,046	2,979,032
9a	2,989,517	-2,890,864	-3,024,918
9b	2,990,717	-2,895,192	2,993,256
10a	2,993,480	-2,897,888	-3,015,768
10b	2,994,006	-2,899,808	3,002,194
11a	2,994,874	-2,900,674	-3,008,962
11b	2,994,874	-2,900,674	3,008,962
12a	2,994,006	-2,899,808	-3,002,194
12b	2,993,480	-2,897,888	3,015,768
13a	2,990,717	-2,895,192	-2,993,256
13a	2,989,517	-2,890,864	3,024,918
14a	2,984,340	-2,886,046	-2,979,032
14b	2,982,121	-2,878,170	3,039,928
15a	2,973,484	-2,870,748	-2,953,912
15b	2,969,566	-2,857,126	3,067,458
16a	2,955,565	-2,846,544	-2,906,406
16b	2,948,677	-2,823,128	3,121,700
17a	2,925,940	-2,809,382	-2,810,972
17b	2,913,713	-2,768,854	3,235,418
18a	2,876,387	-2,754,938	-2,605,868
18b	2,854,418	-2,684,286	3,491,310
19a	2,792,451	-2,685,382	-2,120,872
19b	2,752,257	-2,561,570	4,134,516
20a	2,640,582	-2,629,856	-725,212
20b	2,559,152	-2,402,380	6,210,616
NORMAL	3,018,896	-2,941,384	+3,011,520

Figure 2.4-4. Device Coil Notation for the Loads Shown on Table 2.4-1 and on Figures 2.4-1, 2.4-2, and 2.4-3.

TABLE 2.4-2

EQUILIBRIUM FIELD COIL DESIGN USED FOR
COMPUTATIONS 21, 21A, 21B AND 21C

EF Coil	R(m)	Z ($\pm$ m)	AMP-Turns
1, 2	4.8130	0.4572	-3 x 32,500
3, 4	4.8130	0.5398	-4
5, 6	4.8130	0.6223	-4
7, 8	4.8130	0.7049	-4
9, 10	4.2621	1.5494	-4
11, 12	4.0640	1.5891	-2
13, 14	4.0640	1.6510	-3
15, 16	3.8810	1.7270	-4
17, 18	3.2160	1.9812	-4
19, 20	0.7620	0.1238	6
21, 22	0.7620	0.2069	6
23, 24	0.8382	0.7747	6
25, 26	0.8382	0.8573	6
27, 28	0.8588	0.9398	4
29, 30	1.0478	1.1494	4
Plasma	2.4800	0.0	2,500,000

NOTE: Above signs give (+) values in PDXFORC

TABLE 2.4-3

EQUILIBRIUM FIELD COIL DESIGN (H7) USED FOR
COMPUTATIONS 21D, 21E, 21F AND 21G

EF Coil	R(m)	Z ($\pm$ m)	AMP-Turns
1, 2	4.9	0.554	-2 *80,000
3, 4	4.9	0.662	-2
5, 6	4.9	0.77	-2
7, 8	4.1747	1.5182	-2
9, 10	4.0467	1.5994	-1
11, 12	3.8971	1.7048	-1
13, 14	3.7111	1.8098	-1
15, 16	2.9834	2.1006	-1
17, 18	2.8	2.1276	-2
19, 20	2.2498	1.947	-1
21, 22	1.1564	1.1683	+1
23, 24	0.92875	0.81245	+4
25, 26	0.9478	0.88865	+2
27, 28	0.771	0.1143	+2
29, 30	0.771	0.1905	+2
31, 32	0.771	0.2667	+2
33, 34	0.771	0.3429	+2
* { 35, 36	4.9	0.851	-1
37, 38	2.9834	2.1546	+1
39, 40	2.2498	2.001	+1
41, 42	1.0819	1.0761	+1
43, 44	0.8424	0.5366	-1
Plasma	2.48	0.0	+2,500,000

*Provides Index of Curvature = 0.15

Omit Coils 35 to 44 for Curvature = 0.33

Reverse Amps in Coils 35 to 44 for Curvature = 0.52

TABLE 2.4-4

POLOIDAL FIELD LOADS FROM EQUILIBRIUM FIELD COILS

CONDITION	MOMENT (M) (in. lb)	FORCE (FX) (lb)
Table 2.4.2 EF Plus Plasma	50,639,636 (5.722 MN-m)	473,150 (2.106 MN)
Table 2.4.3 Curv = 0.15 Plus Plasma	53,907,388 (6.091 MN-m)	510,159 (2.268 MN)
Table 2.4.3 Curv = 0.33 Plus Plasma	53,528,940 (6.048 MN-m)	514,350 (2.286 MN)
Table 2.4.3 Curv = 0.52 Plus Plasma	53,150,542 (6.006 MN-m)	518,544 (2.306 MN)
Table 2.4.3 Curv = 0.15 No Plasma	78,370,410 (8.855 MN-m)	761,870 (3.388 MN)
Table 2.4.3 Curv = 0.33 No Plasma	77,992,012 (8.813 MN-m)	766,064 (3.407 MN)
Table 2.4.3 Curv = 0.52 No Plasma	77,613,614 (8.770 MN-m)	770,258 (3.426 MN)

3.0 ANALYSIS RESULTS

The structural evaluations performed on the toroidal field coil have provided predictions of coil deflections and coil stress. The results include the separate effects from toroidal fields, poloidal fields and the thermal expansion of the toroidal field coils as well as the superposition of all the effects for the conceptual design.

3.1 TOROIDAL FIELD COIL DEFLECTIONS

The toroidal field coil motions when described from a device viewpoint result in: (1) device axial expansion and radial contraction from the toroidal field loads, 2) twist about the device centerline from the poloidal field loads, and 3) device axial and radial expansion from the heating in the copper conductors.

3.1.1 Toroidal Field Load Deflections

The computer run for the toroidal field loads is number (30). Under the combined action of 25.84 MN centering force and 26.86 MN of axial tension on each of the V-sections, the coil expansion in the machine axial direction is 0.192 in. (0.448 cm), and the toroidal field coil machine radial centering motion is 0.035 in. (0.088 cm) at the machine inner radius of the TF coil, and the radial centering motion is 0.0372 in. (0.095 cm) at the device outer radius on the TF coil.

3.1.2 Poloidal Field Load Deflections and Sensitivity Study

The design of the V-shaped toroidal field coil is intended for the purpose of replacing what is referred to in past design concepts as the machine torque frame. Consequently a large amount of analysis effort was expended to verify the feasibility of the concept of

integral torque carrying capability for a toroidal field coil under the action of vertical field loads. The parameter of interest or comparison between design concepts is the coil angular rotation. This is referred to in subsequent sections as the copper centroid slope and it is defined simply as the lateral deflection of a point on the copper divided by the distance of that point from the machine horizontal midplane. Comparisons are provided to evaluate the sensitivity of coil angular deflection to three different coil-to-coil bolt patterns, a range of modeled material property variations, shear pin tolerance at the shear panels, coil-to-coil interface bolt tolerances, coil-to-coil interface friction conditions, the load variations for different vertical field indices of curvature and the load variations for equilibrium fields with and without a plasma field. The comparison of computed results is shown on Table 3.1-1 which is supplemented by Figure 3.1-1.

Equilibrium Plus Plasma Field Load Deflections

The results of computations 21, 21A, 21B, 21C and 21D represent a range of possible coil motions for the equilibrium and plasma field designs defined by tables 2.4-2 and 2.4-3 in section 2.4.3 and for the condition of no tolerance on the shear panel assembly pins. Run number (40) to (44) computations show little deflection sensitivity to the bolt patterns and to the range of material properties defined by Table 2.3-1 and 2.3-2. The most influential parameter is shown to be the coil to coil interface friction by comparison of computation 21C with the others. For computation 21C, there is no relative motion at the coil to coil interface. This is achievable by friction forces acting with interface compression or by and interlocking mechanical design. Figure 3.1-2 examines what the combined interface compression and friction coefficient must be to achieve a no slip condition at this interface. The solid curve on Figure 3.1-2 shows the computed shear load distribution on that interface to achieve the no slip condition, and this is direct output from

TABLE 3.1-1
A PARAMETER COMPARISON FOR THE TF COIL
LATERAL DEFLECTION (SLOPE) SENSITIVITY ANALYSIS

Computation Number	Maximum Copper Centroid Slope (milliradians)	Composite Material Shear Modulus (GPa)	Epoxy Radial Fill Thickness	Epoxy Lateral Fill Thickness	Bolt Pattern At Coil Angular Location* (θ , Degrees)	Bolt Tolerance	Magnetic Field Crossing the TF Coil Current and Coil Moment about Copper, Hor. $\underline{Q}$	Coil Interface Condition
21	2.67	1.53×10^6 psi (10.5 GPa)	0.200 in. (0.508 cm)	0.100 in. (0.254 cm)	13 Bolts at 0 +20 +40 +60 +80 +100 +120	PERFECT FIT	EF + Plasma 50.64×10^6 in-lb (5.72 MN-m)	** No Friction
21A	2.72							
21B	2.67		0.050 in. (0.127 cm)					
21C	0.79		0.100 in. (0.254 cm)					No Slip
21D	2.59				13 Bolts at 0 +4 +20 +40 +60 +88 +120	0.006 in. (0.015 cm)	EF + Plasma 53.90×10^6 in-lb (6.1 MN-m)	** No Friction
21E	3.86		0.404 in. (1.016 cm)	0.354 in. (0.900 cm)			EF, No Plasma 78.37×10^6 in-lb	
21F	4.05						(8.85 MN-m)	
21G	3.82				13 Bolts at 0, +4, +20, +44, +68, +92, +120	PERFECT FIT		

*The coil angular location, $\theta = 0$ is at the maximum machine radius as indicated on Figure 4.

**The bolts carry all shear load.

Figure 3.1-1. Toroidal Field Coil Slope Versus Coil Angular Location for Various Vertical Field Loads of Table 3.1-1.

Figure 3.1-2. TF Coil-to-Coil Interface Load Distributions

computation 21C, computer run (43). This shear load must be less than the sum of the normal loads multiplied by a coefficient of friction for a no slip condition. The normal load distributions are shown as the non solid curves. The dotted curve is the compressive load distribution at the coil to coil interface arising from the mutual attraction between the two copper pancakes induced by the toroidal field. This mutual attraction corresponds to a compressive stress of about 350 psi (2.4 MPa) over the coil-to-coil interface area. The load information source is run number (9). The dashed curve represents an average wedge compression of about 52,000 lbs/degree induced by the centering force from the toroidal field load computed in number (9). This corresponds to a compressive stress of about 2100 psi (14.4 MPa) averaged over the coil-to-coil interface area. Figure 3.2-4 shows the distribution of compressive stress from wedging to be concentrated toward the machine centerline, and therefore this would be the region to receive the most benefit from interface loading that helps prevent interface slip. A more accurate distribution of this interface load could be obtained by scaling the 52,000 lbs/degree by the ratio of stress shown on Figure 3.2-4, View Plane ①, to the average stress of 2100 psi (14.4 MPa). The dash-dot curve represents the average interface compression that is achieved by loading 6-1/2, 2-inch (5.08 cm) diameter bolts to a preload of 100,000 psi (689 MPa). If the coil lateral deflection of 2.5 to 3.0 milliradians which is based on no interface friction is judged to be unacceptable, a more detailed evaluation of required friction coefficients should be conducted with the above load information descriptions.

Equilibrium (without Plasma) Field Load Deflections

The results of computations 21E, 21F and 21G, computer runs (45) to (47) provide two comparisons. The first comparison between 21E and 21G shows that the two different bolt patterns has little effect upon lateral deflection. In later sections it will be shown that the importance of bolt locations is more influenced by the individual bolt shear loads than by the effect upon coil deflection. The comparison provided by computations 21E and 21F would indicate that coil lateral deflection increases by about 5% for the bolt tolerance shown. The assumptions for computation 21F was a 6 mil (0.015 cm) clearance between the bolt and

the coil flange. Each node point on the finite element model that represented a bolt location was free to move half of the clearance in a direction of the computed shear load on each bolt from the prior computation 21E.

Rigid Body Deflections

The following is a simplified hand calculation to account for shear panel assembly tolerances. It is conservatively assumed here that the toroidal field coil is free to deflect laterally if the shear panels are not acted upon. It is also conservatively assumed that all of the shear panel pins are centered in oversized holes in the panels. The unrestrained rotation of the TF coil is then that in taking up the tolerance. This rotation is then equal to the diametral pin clearance divided by the distance between pins that make panel contact upon rotation. With a 4 mil (0.010 cm) tolerance on the pin diameter, and with a 16-in. (40.64 cm) space between pins, the TF coils could as an upper bound rotate an additional 0.25 milliradians prior to shear panel action.

Combined Poloidal Field Coil Lateral Deflections

Using computation 21D as a baseline, the upper limit for conceptual design coil angular rotation for the operating condition of equilibrium plus plasma fields crossing the TF coil current is with assembly tolerances $(2.59 + 0.05 * 2.59 + 0.25) \cong 3$ milliradians. Based upon computation 21C, the lower limit is (0.79) about one milliradian.

3.1.3 Thermal Deflections

The computer run for thermal deflections is number (48). Under the thermal condition defined in Section 2.4.5, the TF coil expansion in the machine axial direction is 0.047 in. (0.119 cm), and the device diametral expansion computed at the outer radius on the TF coil is 0.052 in. (0.132 cm).

3.2 TOROIDAL FIELD COIL STRESSES

The toroidal field coil stress behavior has been evaluated for the separate and combined conditions of equilibrium field with no plasma, toroidal field, and thermal field. A summary of the predicted coil stresses and deflections for these load conditions is provided in Table 3.2-1. Here the principal stresses and the maximum shear stresses are provided for the steel structure and the copper winding. Also, for the different load conditions, the TFTR device deflections discussed in Section 3.1 are given on Table 3.2-1. The stresses shown for the separate load conditions (computations 21H, 21I, and 21J) occur at different locations, and therefore they are not additive. The combined primary stresses produced by the superposition of the magnetic field loads are provided by computation 21K. The superposition of thermal stress with the primary stress from the equilibrium and toroidal fields is indicated as computation 21J + 21K.

3.2.1 Equilibrium Field With No Plasma

The results of computation 21H, computer run (49), were produced from shear and deflection boundary conditions only. That is, the node point loads from the equilibrium field crossing the TF coil current were not used. The output from computation 21, run (47), defined by Table 3.1-1 was used as the loading condition for computation 21H. A comparison of computed stress by computations 21G and 21H showed excellent agreement as less than 1% difference at the finite elements of significant ($<5,000$ psi) stress. The maximum of 15,291 psi (105 MPa) shear stress shown on Table 3.2-1 for this load condition, results from the action of the bolts into the flanges of the coil steel container. The isostress plot on Figure 3.2-1 shows the amplified stress patterns near the simulated bolt location. The maximum principal stress of 29,897 psi (206 MPa) is a result of combined shear and bending stress in the steel box sidewall and at the common shear plane formed by the vertical midplane of a single TF coil. The isostress plot of maximum principal stress at these locations is provided on Figure 3.2-2. The bolt shear loads for the condition of equilibrium field with no plasma are shown on Tables 3.2-2, 3.2-3, and 3.2-4 for computations 21E, 21F, and 21G. The 21E and 21G comparison is for two different bolt patterns, and the 21E compared to 21F shows the effect of bolt tolerance.

TABLE 3.2-1

A PARAMETER COMPARISON FOR THE TF COIL
COMBINED STRESS AND LOAD SENSITIVITY ANALYSIS

		Stress				Deflection	
		Steel Structure		Copper Winding			
Comp. Number	Load Conditions	Maximum Principal Minimum Principal Maximum Shear (psi) (MPa)		Maximum Principal Minimum Principal Maximum Shear (psi) (MPa)		At Coil Top, Device Axial Direction	At Coil Outer Radius in Device Radial Direction
21H	Equilibrium Field (No Plasma)	29897 206 -19158 -132 15291 105		5617 39 -7197 -50 3661 25		0.00	0.00
21I	Toroidal Field	38480 265 -30029 -207 23615 162		17545 121 -7595 -52 9690 67		0.192 in. (0.488 cm)	-0.0372 in. (-0.095 cm)
21J	Thermal	23454 162 -5919 41 12532 86		469 32 -7925 -55 3103 21		0.047 in. (0.119 cm)	0.026 in. (0.066 cm)
21 K = 21I + 21G —	Equilibrium & Toroidal	56959 391 -30077 -207 25819 178		17907 124 -7600 -52 9950 69		0.192 in. (0.488 cm)	-0.0372 in. (-0.095 cm)
21J + 21K	Primary + Thermal	72146 497 -26457 -182 32552 225		13212 91 -10476 -73 9104 63		0.239 in. (0.607 cm)	-0.0112 in. (-0.029 cm)

Figure 3.2-1. Toroidal Field Coil Maximum Shear Stress, psi (MPa), from Equilibrium Field Load and No Plasma, Computation 21H, Viewing Plane ①, and Viewing Plane Definitions for all Isostress Plots

Figure 3.2-2. Toroidal Field Coil Maximum Principal Stress, psi (MPa), from Equilibrium Field Load and No Plasma, Computation 21H

TABLE 3.2-2

TF COIL BOLT SHEAR LOADS FROM
EQUILIBRIUM FIELD LOADS, COMPUTATION 21E

Bolt Location (θ , degrees)	Y-Direction Force (lb)	Z-Direction Force (lb)	Resultant Force (lb)
0	0 0	-152,588 (678.7 kN)	152,588 (678.7 kN)
+4	5,109 (22.72 kN)	-127,555 (567.3 kN)	127,657 (567.8 kN)
+20	47,969 (213.3 kN)	-97,576 (434.0 kN)	108,729 (483.6 kN)
+40	91,661 (407.7 kN)	-73,502 (326.9 kN)	117,491 (522.6 kN)
+60	166,517 (740.6 kN)	-44,711 (198.8 kN)	172,415 (766.9 kN)
+88	195,457 (869.4 kN)	-23,142 (102.9 kN)	196,822 (875.4 kN)
+120	48,350 (215.0 kN)	-157,313 (699.7 kN)	164,575 (732.0 kN)

TABLE 3.2-3

TF COIL BOLT SHEAR LOADS FROM
EQUILIBRIUM FIELD LOADS, COMPUTATION 21F

Bolt Location (θ , degrees)	Y-Direction Force (lb)	Z-Direction Force (lb)	Resultant Force (lb)
0	0 0	-150,218 (668.1 kN)	150,218 (668.1 kN)
+4	6,167 (27.43 kN)	-125,879 (559.9 kN)	126,029 (560.5 kN)
+20	47,063 (209.3 kN)	-96,212 (427.9 kN)	107,105 (476.4 kN)
+40	88,549 (393.8 kN)	-73,865 (328.5 kN)	115,312 (512.9 kN)
+60	160,938 (715.8 kN)	-48,970 (217.8 kN)	168,223 (748.2 kN)
+88	187,887 (835.7 kN)	-30,466 (135.5 kN)	190,341 (846.6 kN)
+120	63,508 (282.4 kN)	-148,661 (661.2 kN)	161,658 (719.0 kN)

TABLE 3.2-4

TF COIL BOLT SHEAR LOADS FROM
EQUILIBRIUM FIELD LOADS, COMPUTATION 21G

Bolt Location (θ , degrees)	Y-Direction Force (lb)	Z-Direction Force (lb)	Resultant Force (lb)
0	0 0	-156,556 (696.3 kN)	156,556 (696.3 kN)
+4	5,156 (22.93 kN)	-130,476 (580.3 kN)	130,577 (580.8 kN)
+20	50,041 (222.6 kN)	-102,160 (454.4 kN)	113,757 (506.0 kN)
+40	103,431 (460.0 kN)	-71,910 (319.8 kN)	125,972 (560.3 kN)
+68	195,524 (869.7 kN)	-38,514 (171.3 kN)	199,281 (886.4 kN)
+92	164,070 (729.8 kN)	-19,064 (84.79 kN)	165,173 (734.7 kN)
+120	41,785 (185.8 kN)	-151,525 (673.9 kN)	157,180 (699.1 kN)

The condition of equilibrium field with no plasma produces the worst shear condition in the shear panel shear pins. A very conservative calculation gives a pin shear stress of 116,000 psi (800 MPa) with a pin diameter of 1.5-in. (3.82 cm) and with a coil moment of 78.37×10^6 in-lb (8.85 MN-m). The conservative assumptions here included only one set of shear panels instead of four, only four pins per panel instead of eight, and the two pins on each side of the panel were chosen as the two closest together so as to produce the maximum shear in resisting the panel moment.

3.2.2 Toroidal Field Loads

The results shown in Table 3.2-1 for computation 21I, run number (50), were produced by application of the loads defined in Section 2.4.1 produced by the toroidal field crossing a single TF coil with 3,200,800 amp-turns. The maximum principal stress shown for the steel (265 MPa) and the copper winding (121 MPa) results from the primary axial tension and bending through the coil cross-section at the device horizontal midplane in the region of wedging. These stresses are a maximum at the respective material inner radial surfaces. The isostress plots of this component of stress are given on Figure 3.2-3 for the steel and copper. The minimum principal stresses in the steel (-207 MPa) and copper (-52 MPa) are from wedge compression. The isostress plots for this component of stress are shown on Figure 3.2-4 as the model X-direction component of stress. Some representative Y-direction components of stress for the toroidal field loads are given on Figure 3.2-5.

3.2.3 Thermal Loads

The assumed thermal loading condition was that of uniform temperature in the windings and in the steel portions of the toroidal field coil with the copper being 33°C hotter than the steel. The resultant stresses for this computation 21J, run number (48), model shows on Table 3.2-1 a maximum compression in the copper of 7595 psi (-52 MPa) and tension in the steel of 23,454 psi (162 MPa). The isostress plot for minimum principal stress in the copper is shown on Figure 3.2-6, and some plots for maximum principal stress in the steel are provided on Figure 3.2-7.

Figure 3.2-3. Toroidal Field Coil Z-Direction Stress, psi (MPa), from Toroidal Field Load, Computation 211

Figure 3.2-4. Toroidal Field Coil X-Direction Stress, psi (MPa),
from Toroidal Field Load, Computation 211

Figure 3.2-5. Toroidal Field Coil Y-Direction Stress, psi (MPa),
from Toroidal Field Load, Computation 211

Figure 3.2-6. Toroidal Field Coil Minimum Principal Stress, psi (MPa),
from Thermal Load, Computation 21J

Figure 3.2-7. Toroidal Field Coil Maximum Principal Stress, psi (MPa), from Thermal Load; Computation 21J

3.2.4 Combined Toroidal and Poloidal Field Loads

Section 2.2.4 outlined two ways from which the combined field loads could be obtained, and both methods were used. The results from the more accurate method are presented in this report. This is algebraically adding the stress components from the individual cases and then recomputing the principal stress and the maximum shear stress from the new stress components based upon superposition. The results from the second method are not what was expected and are briefly discussed here because the specific reason for inaccuracy has not been determined other than it resulted from finite element method error or undetected input error or a misapplication of the finite element method. This latter method was to apply the toroidal field node point loads simultaneously with some shear and displacement conditions computed at the horizontal and vertical boundary planes of the TF coil model from the poloidal field load analysis results. These computations were computer runs (51) and (52). Computer run (51) was the toroidal load plus the boundary conditions from the poloidal field results. The expected coil inward radial motion is about $-.037$ in ($-.095$ cm), and the computed value here was $-.053$ in ($-.135$ cm). The computer run (52) computation was the toroidal load plus the negative of boundary conditions from the poloidal field analysis results. The expected coil inward motion is again $-.037$ in ($-.095$ cm), and the computed value here was $-.043$ in ($-.110$ cm).

The results shown in Table 3.2-1 for computation 21K are from direct superposition and the computer run numbers are (53) and (54). By comparison with computation 21H or 21I on Table 3.2-1, the increase of maximum principal stress is directly attributed to the superposition of tension and bending in the steel from the toroidal and poloidal fields. Figure 3.2-8 shows the distribution of Z-direction stress in the steel and Figure 3.2-9 shows the Y-direction isostresses in the steel.

The result comparison on Table 3.2-1 between 21I and 21K shows little difference for the copper windings. Some representative Z-direction and Y-direction isostress plots are shown on Figures 3.2-10 and 3.2-11 for the copper section of the coil under combined

Figure 3.2-8. Toroidal Field Coil Z-Direction Stress, psi (MPa), from Toroidal Plus Equilibrium Field Load, Computation 21K

Figure 3.2-9. Toroidal Field Coil Y-Direction Stress, psi (MPa), from Toroidal Plus Equilibrium Field Load, Computation 21K

Figure 3.2-10. Toroidal Field Coil Z-Direction Stress, psi (MPa), from Toroidal Plus Equilibrium Field Load, Computation 21K

Figure 3.2-11. Toroidal Field Coil Y-Direction Stress, psi (MPa), from Toroidal Plus Equilibrium Field Load, Computation 21K

toroidal and poloidal field loads.

The maximum value of the maximum shear stress computed in the coil shear panels in run (53) by the finite element model was 13772 psi (95 MPa). If a single set of panels instead of four carry the entire shear through 100 in^2 (646 cm^2) of panel, the average shear stress is 750 psi (5.2 MPa) for a panel reacting the TF coil moment from the equilibrium field with no plasma.

3.2.5 Combined Primary and Thermal Loads

The results shown on Table 3.2-1 for the stress from the combined loading conditions was obtained from the superposition of stress components from the equilibrium field loads, the toroidal field loads and the effect of temperature differences. The computer run numbers are (55) and (56). The net effect of the additional tension in the steel is observed by comparing Figures 3.2-12 and 3.2-13 with 3.2-8 and 3.2-9. The compression effect upon stress in the copper windings is observed by comparing Figures 3.2-14 and 3.2-15 with 3.2-10 and 3.2-11. Figure 3.2.16 shows the maximum principal stress in the steel side wall for the combined load conditions. The approximate contributions to the peak value of 497 MPa shown on Figure 3.2.16 is (72,146 psi = 28,100 psi EF plus 28,300 psi TF plus 15,700 psi thermal).

3.3 INTERPRETATIONS OF ANALYSIS RESULTS

The detailed stress analysis results obtained from the finite element solution method represent the idealized behavior of homogeneous Hookean materials. Similarly, the results characterize the behavior of the model geometry which does not completely detail the conceptual design geometric configuration. The differences between modeled materials, the real materials, modeled geometry and the real geometry are identified here for the purpose of putting the

analysis results into a proper perspective, as well as for identifying areas where modeling refinements can be incorporated into the preliminary design analysis.

3.3.1 Interpretations of Analysis Results for Stainless Steel Regions of Structure

The material property assumptions relating to liner-elasticity, homogeneity and isotropy are considered accurate for the structural steel portions of the model where predicted stresses are at or below the material proportional limit. The reactions of the steel portions of the TF coil to loads from the winding portion of the TF coil are likewise judged to be accurate on the basis that the finite element model was calibrated to accurately predict the gross coil deflections from the experience gained by the PLT finite element analysis predictions that were fine-tuned to match the PLT experimentally measured deflections.

The geometric variances of the steel portions of the model when compared to the conceptual design drawings occurred at the coil-to-coil bolt flanges and at the shear panel flange connections with both the shear panels and the steel box side walls. Neglecting the bolt flanges was a conservative assumption, because it resulted in smaller moment arms to resist the poloidal field overturning moments; and therefore, the computed bolt shear loads are on the high side. The location of maximum predicted stress (see Figure 3.2-16) on the steel box side wall was at a transition region of panel-stiffened side wall to unstiffened side wall allowing for the model to predict a large local bending stress at that transition. Since the model does not accurately represent the true geometric locations for panel flange connections, the predicted stress may not be representative of true behavior. The simple check to see if the model is creating the stress riser is to relocate the second (counting radially inward) shear panel on the model to raise it from the same horizontal plane as the outer modeled panel. This would be more representative of the panel locations shown on Figure 2.1-3. If the new model still predicts but only relocates the high stress region, then design modifications to include tapered panel flanges could be modeled to

demonstrate that this highly stressed location can be modified to be stressed at a relatively low value when compared to the prediction at the horizontal midplane of the coil.

The maximum principal stress prediction of 342 MPa (49,648 psi) shown at the horizontal midplane in the wedge region on Figure 3.2-16 is judged to be the location on the steel structure that will provide the comparison with allowable stresses in the stainless steel for ultimately making the preliminary and final design adequacy decision. The predicted primary stress at this location shown on Figure 3.2-8 is 260 MPa (37,600 psi) from the combined toroidal and equilibrium field loads. The predicted primary plus thermal stress is shown on Figure 3.2-12 as 340 MPa (49,354 psi). For comparison to the conceptual design analysis results, some reported strength values for Armco 18-3 Mn stainless steel are:

$$0.2\% \text{ YS} = 379 \text{ MPa (55,000 psi)}$$

$$\text{UTS} = 689 \text{ MPa (100,000 psi)}$$

$$\text{Fatigue} = 331 \text{ MPa (48,000 psi) at } 10^8 \text{ cycles}$$

3.3.2 Interpretations of Analysis Results for the Copper/Epoxy Windings

The winding portion of the toroidal field coil was modeled as a homogeneous, linear-elastic material with an approximation to account for anisotropy. There is a significant difference between this and the true laminated nature of this structure where predictions show the stress results to be in a range beyond the linear-elastic limit for annealed OFHC. The finite element model of this structure was calibrated from comparisons with the PLT predictions and measurements to accurately predict the gross coil deflections. This was achieved by adjusting the laminate weak direction shear modulus in an unlaminated or homogeneous model. Since the model was not a laminated structure of alternating copper and epoxy, the stress distributions from bending are judged to be both inaccurate and conservatively high. By

comparison, the maximum predicted stress on the PLT windings by the finite element model is about 193 MPa (28,000 psi) when a strain gage measurement only indicates a stress of 83 MPa (12,000 psi).

The maximum principal stress computed for the winding portion of the structure is shown on Figure 3.2-10 to be at the horizontal midplane in the wedge region from the primary loads imposed by the combined toroidal and equilibrium fields. The membrane stress (neglecting thermal compression) through this cross section is about 69 MPa (10,000 psi). Bending changes this to a predicted bending plus membrane stress of about 122 MPa (17,676 psi) shown on Figure 3.2-10. Under similar deflections, the bending stress of a laminated beam is lower than that of a solid beam of equal total beam thickness because of the differences in the moment of inertia of the two sections. Both this and the PLT experimental comparison would indicate that the bending stress predictions for the copper windings are high. For comparison to the conceptual design analysis results, a reported fatigue strength for annealed OFHC is about 117 MPa (17,000 psi) for 100,000 cycles of complete stress reversal.

An additional irregularity not modeled in the windings is the coolant holes which result in reduced cross-sections, stress concentrations, and additional non-uniformity of thermal gradients. This feature impacts the stress prediction shown on Figure 3.2-4, as well as an additional thermal compression of about 27.5 MPa (4,000 psi) that is additive to the stress shown for the windings on Figure 3.2-4. At the holes the copper area is reduced by a factor of 2.65 and with a stress concentration factor of 2.1 these stresses can be magnified by a factor of 5.6. This is far beyond the elastic range and will result in localized inelastic flow in the regions of the coolant holes. At worst there would be about a 12 mil reduction on the 375 mil hole diameters. If further analyses show that a hole reduction or that stress and fatigue is detrimental here, a relief machined from the copper at the mating interfaces in the wedge region could be provided to eliminate the primary wedge compression by transferring it to the steel flanges of the TF coil.

Figure 3.2-12. Toroidal Field Coil Z-Direction Stress, psi (MPa), from Combined (Toroidal + Equilibrium + Thermal) Field Loads, Computation (21J + 21K)

Figure 3.2-13. Toroidal Field Coil Y-Direction Stress, psi (MPa), from Combined (Toroidal + Equilibrium + Thermal) Field Loads, Computation (21J + 21K)

Figure 3.2-14. Toroidal Field Coil Z-Direction Stress, psi (MPa), from Combined (Toroidal + Equilibrium + Thermal) Field Loads, Computation (21J + 21K)

Figure 3.2-16. Toroidal Field Coil Maximum Principal Stress, psi (MPa), from Combined (Toroidal + Equilibrium + Thermal) Field Loads, Computation (21J + 21K)

4.0 REFERENCES

1. Swanson, J. A. and DeSalve, G. J., ANSYS, Engineering Analysis Systems User's Manual, October 1, 1972, Elizabeth, Pennsylvania 15037.
2. Smith, R. A., Finite Element and Node Point Generation Computer Programs Used for the Design of Toroidal Field Coils in Tokamak Fusion Devices, WFPS-TME-001, June 30, 1975, Westinghouse Electric Corporation, P. O. Box 10864, Pittsburgh, Pa. 15236.
3. Smith, R. A., Field Load and Displacement Boundary Condition Computer Program Used for the Finite Element Analysis and Design of Toroidal Field Coils in a Tokamak, WFPS-TME-002, June 30, 1975, Westinghouse Electric Corporation, Fusion Power Systems Department, P. O. Box 10864, Pittsburgh, Pa. 15236.
4. Toroidal Field Coil Assembly, Westinghouse Drawing No. 346838J.

APPENDIX A
COMPUTER RUN NUMBERS

1. Computer Program PDXNODE, Run Number WMT C11B, 3-12-75.
2. Computer Program PDXNODE, Run Number WMT C21I, 3-13-75.
3. Computer Program PDXNODE, Run Number WMT C1WW, 4-9-75.
4. Computer Program PDXNODE, Run Number ANRA16J, 7-2-75.
5. Computer Program PDXNODE, Run Number ANRA1FJ, 9-2-75.
6. Computer Program PDXNODE, Run Number ANRA1B4, 9-3-75.
7. Computer Program PDXNODE, Run Number ANRA1FI, 9-9-75.
8. Computer Program ELEMENT, Run Number ANIRA02, 8-5-75.
9. Computer Program PDXFORC, Run Number WMT C62C, 3-13-75.
10. Computer Program PDXFORC, Run Number ANRA2PY, 7-15-75.
11. Computer Program PDXFORC, Run Number ANRA26S, 7-14-75.
12. Computer Program PDXFORC, Run Number ANRA23G, 7-15-75.
13. Computer Program PDXFORC, Run Number ANRA2QX, 7-15-75.
14. Computer Program PDXFORC, Run Number ANRA3RM, 7-15-75.
15. Computer Program PDXFORC, Run Number ANRA1HH, 7-18-75.
16. Computer Program PDXFORC, Run Number ANRA3PR, 7-18-75.
17. Computer Program PDXFORC, Run Number ANRA5QC, 7-18-75.
18. Computer Program PDXFORC, Run Number ANRA7RH, 7-18-75.
19. Computer Program PDXFORC, Run Number ANRA9M6, 7-22-75.

20. Computer Program PDXFORC, Run Number AN2RATU, 7-19-75.
21. Computer Program PDXFORC, Run Number AN4RAT7, 7-19-75.
22. Computer Program PDXFORC, Run Number AN6RAUZ, 7-19-75.
23. Computer Program PDXFORC, Run Number ANRA1Y8, 7-17-75.
24. Computer Program PDXFORC, Run Number AN7RAU9, 7-19-75.
25. Computer Program PDXFORC, Run Number AN5RAUT, 7-19-75.
26. Computer Program PDXFORC, Run Number AN3RATZ, 7-19-75.
27. Computer Program PDXFORC, Run Number AN1RATH, 7-19-75.
28. Computer Program PDXFORC, Run Number ANRA8SG, 7-19-75.
29. Computer Program PDXFORC, Run Number ANRA6ML, 7-22-75.
30. Computer Program PDXFORC, Run Number ANRA4P9, 7-18-75.
31. Computer Program PDXFORC, Run Number ANRA2H7, 7-18-75.
32. Computer Program PDXFORC, Run Number WMTCl1R, 3-26-75.
33. Computer Program PDXFORC, Run Number ANRA315, 9-8-75.
34. Computer Program PDXFORC, Run Number ANRA214, 9-8-75.
35. Computer Program PDXFORC, Run Number ANRA1GT, 9-5-75.
36. Computer Program PDXFORC, Run Number ANRA4D8, 9-9-75.
37. Computer Program PDXFORC, Run Number ANRA5ED, 9-9-75.
38. Computer Program PDXFORC, Run Number ANRA6EG, 9-9-75.
39. Computer Program ANSYS, Run Number ANRA28N, 9-17-75.
40. Computer Program ANSYS, Run Number ANRA189, 8-6-75.
41. Computer Program ANSYS, Run Number ANRA2A3, 9-2-75.

42. Computer Program ANSYS, Run Number ANRA2B5, 9-3-75
43. Computer Program ANSYS, Run Number ANRA30W, 9-4-75
44. Computer Program ANSYS, Run Number ANRA1KR, 9-11-75
45. Computer Program ANSYS, Run Number ANRA2NT, 9-11-75
46. Computer Program ANSYS, Run Number ANRA2U2, 9-12-75
47. Computer Program ANSYS, Run Number ANRA2UZ, 9-12-75
48. Computer Program ANSYS, Run Number ANRA2YG, 9-19-75
49. Computer Program ANSYS, Run Number ANRA26Z, 9-18-75
50. Computer Program ANSYS, Run Number ANRA28N, 9-17-75
51. Computer Program ANSYS, Run Number ANRA3RK, 9-26-75
52. Computer Program ANSYS, Run Number ANRA2SS, 9-26-75
53. Computer Program ANSYS, Run Number ANRA1HM, 10-7-75
54. Computer Program ANSYS, Run Number ANRA115, 10-8-75
55. Computer Program ANSYS, Run Number ANRA21X, 10-6-75
56. Computer Program ANSYS, Run Number ANRA2U1, 10-8-75