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STRESS ANALYSIS OF THE CONCEPTUAL DESIGN
CONFIGURATIONS OF CONSTANT TENSION D-SHAPED
SUPERCONDUCTING TOROIDAL FIELD COILS
FOR TNS

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September 30, 1977

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SUPERCONDUCTING TOROIDAL FIELD COILS
FOR TNS

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ABSTRACT

Conceptual design configurations of D-shaped toroidal field coils applicable to the TNS program are studied under the action of the toroidal field loading condition and the vertical field loading condition, but not the fault condition. Although the analysis is specific to an 8 Tesla design using a niobium titanium superconductor, the results can be extended to a coil with a different conductor material and subjected to a field of different magnitude provided the condition of linear elasticity is not violated. The analysis technique used is the finite element method, with three dimensional finite elements defined in the ANSYS computer code, and supplemented by closed form analytical solutions.

The thermal stresses due to the differential thermal expansions of the support structure material and the conductor material are considered in the closed form solutions, but not in the finite element analyses. Therefore, any strain relief in the conductor or additional stress in the structure due to the differential thermal expansions is accounted for by a separate superposition.

If steel is used as the conductor support material, the strain in the superconductor is 0.144% and the maximum stress in the steel due to stress concentrations is 138308 psi; due to TF loading only. By appropriately re-positioning the individual segments along the length of the coil cross-section, tension is distributed in an optimum manner among the segments and the superconductor strain reduces to 0.074% while the maximum stress in the steel decreases to 75,198 psi.

Aluminum can be used as a suitable support structure material if the coil cross-section area is increased 52% and the pancake positioning is optimized. This results in a superconductor strain of 0.1% and a maximum stress of 50,000 psi in the aluminum due to TF loading alone.

The analysis indicates that a flexible coupling (for example: axial load carrying spokes) between the coil and dewar is more desirable than rigid coupling.

If wedging is used as a means of vertical leg restraint, the bolt diameters in the vertical leg should be 1.42 inches to limit the bolt shear stress to 50,000 psi. This assumes a coefficient of friction of 0.1 between pancakes, and considers TF loading only.

If the bucking cylinder is used as a means of vertical leg restraint, its wall thickness should be 10 inches.

The analyses show that there is no substantial advantage in using a bucking cylinder over wedging as a means of restraining the vertical leg; although the stresses and displacements are slightly lower when a bucking cylinder is used.

The analyses also show that a combination of circumferential and radial shear panel lateral support structure is desirable.

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NOMENCLATURE

b	half length of coil vertical leg
c	number of rows of bolts
C, SS, H	subscript denoting conductor, support structure, and helium coolant holes, etc.
d	number of bolts in every row
e	factor depending on the shape of the coil cross-section
f	correction term
f_1, f_2	design factors of safety
p	external pressure on the bucking cylinder
P_{cr}	critical buckling pressure
th	subscript denoting thermal
r_i, r_o	inner and outer radii of the bucking cylinder
w	side of equivalent square cross-section
x, y, z	cartesian coordinates
x', y'	cartesian coordinates perpendicular to and along wedge face
A	cross-section area
B	ratio of highest stress to average stress in coil cross-section due to TF loading.
D	diameter of bolts
E	Young's modulus
F	constant tension across cross-section
H_{max}	maximum vertical height of coil
I	ampere turns per coil
N	total number of pancakes in coil cross-section
M	number of load carrying pancakes in coil cross-section ($M < N$)
R	distance from machine axis, when used as a coordinate
R	(Force/Length), centering line force due to in-plane loading
S	number of coils
T_f, T_o	final and initial temperatures

α	wedge angle
γ	linear coefficient of thermal expansion
θ, ϕ	circumferential angles
ϵ	strain
σ	normal stress
τ	shear stress
ν	Poisson's ratio
μ	coefficient of friction
μ_0	permeability of free space

1.0 INTRODUCTION

This work studies the structural analysis of different conceptual design configurations of a D-shaped toroidal field coil with application to the TNS program. Although the analysis is specific to a low field (8 Tesla) design using a niobium titanium superconductor the results can be extended to a coil with a different conductor material and subjected to a field of larger magnitude, provided the assumption of linear elasticity is not violated. Consequently the analysis methods and modeling techniques used herein can be used to analyze the different coils currently under consideration in the TNS program, i.e., D-shaped coils using a copper conductor, a niobium titanium superconductor, a niobium tin superconductor, and a hybrid conductor consisting of niobium titanium with a copper insert.

The primary analysis objective was to make pertinent design recommendations concerning the conditions under which steel or aluminum can be used as a suitable conductor support structure material while considering the effect of stress concentrations and allowable values for the magnitude of the strain in the superconductor. Other analysis objectives were to determine how closely the basic D-shaped coil under consideration conforms to a constant tension shape, with no bending across all cross-sections of the coil under the action of the in-plane loading; to make a determination on the optimum location(s) and shape(s) of the coil lateral support structure to withstand the out-of-plane forces and overturning moments; to obtain estimates of the comparative advantages of using either a bucking cylinder or wedging as methods of restraining the vertical leg of the coil; and to obtain the stresses and displacements in the coil system under the action of the combined loads.

An array of sixteen toroidal field coils, each having the 'constant tension' D-shape, (Reference 1), is arranged in a circle of constant radius about the machine axis. The loading on each coil is of two types. The first is the toroidal field loading on the coil (which results in in-plane forces) and is computed as the vector cross-product of the current of 8.54 mega-ampere turns through the coil and the magnetic field induced by the current in each coil. The second is the vertical field loading on the coil (which results in out-of-plane forces and overturning moments) and is computed as the vector cross-product of

the current of 8.54 mega-amp turns and an applied constant vertical magnetic field of 0.5 Tesla. A third loading condition which could arise is a consequence of one of the coils undergoing the fault condition of short circuit and results in both in-plane and out-of-plane forces, but no overturning moments, in all the coils except the shorted coil. The fault loads are obtained, for a specific coil, as the vector cross-product of the current through the coil and the magnetic field induced by the currents in each of the coils except the shorted coil. Unlike the toroidal field forces and the vertical field forces, the fault forces are not the same in every coil but depend on the relative location of the coil from the shorted coil.

Essentially three different conceptual design configurations were studied. The first was that of the basic D-shaped coil, without dewar or lateral support structure (see Figure 6-1), subjected to in-plane loads to determine the effect of stress concentrations on the conductor support structure, the strains in the superconductor, the shear in the bolts holding together the pancakes in the coil cross section, the feasibility of wedging as a means of restraining the vertical leg, and to determine whether the coil represented a constant tension shape. The second was that of the coil system which included the basic D-shaped coil, the dewar, and the shear panel lateral support structure (Figure 6-5), subjected to in-plane, out-of-plane, and combined loads. The shear panel location here was established from the consideration that the circumferential space covered by the angular location $0 \leq \theta \leq 45^\circ$ (see Figure 6-5) is to be reserved for the location of the neutral beam window. The third was that of the coil system shown in Figure 6-7 subjected to both in-plane and out-of-plane loads. The shear panel location here was established with the intent of determining the extent of lateral support structure necessary to keep the coil lateral displacements and slopes within meaningful bounds. The latter two design configurations were also studied to obtain information on the relative merits of rigidly coupling versus decoupling the in-plane forces and the lateral support structure, and to compare the relative advantages of using either a bucking cylinder or wedging as a means of restraining the vertical leg of the coil.

Section 2.0 contains a description of the analysis methods and the analysis models. Section 3.0 summarizes the pertinent results of the various computations and contains a chapter on the interpretation of these results to advance the conceptual design of the coil to the preliminary stage. Section 4.0 contains a detailed documentation of the results of the various analyses and Section 5.0 presents the pertinent bibliography. All of the tables and figures that are referred to in the text of Sections 1.0, 2.0 and 3.0 are presented in Section 6.0.

2.0 DESCRIPTION OF ANALYSIS METHODS AND MODELS

The stress analysis of the superconducting toroidal field coil is based on the finite element method with supplementary closed form solutions. The analyses considered the toroidal field loading and the vertical field loading, but not the fault loading condition.

A description of the numerical methods is presented in Section 2.1. Section 2.2 contains a description of the finite element analysis models while Section 2.3 makes a brief statement on the interpretation of the results of these models. The closed form analysis methods, which supplement the finite element analyses, are presented in Section 2.4

2.1 NUMERICAL ANALYSIS METHODS

The closed form analysis methods used are described in Section 2.4.

The finite element method of solution is based on the ANSYS finite element computer code, Reference (2). The super conducting toroidal field coil geometry (Figure 6-1), conforming to the constant tension D-shape (Reference 1), was approximated by two ellipses in the regions $0 \leq \theta \leq 90^\circ$ and $0 \leq \phi \leq 90^\circ$ and by a straight leg in the region $0 \leq Z \leq Z_0$ in the computer program PDXNODE. The finite elements, into which the coil is divided, are represented as three dimensional solids each of whose node points have three degrees of translational freedom. The toroidal field forces resulting from a current of 8.54 mega-amp turns through each of the sixteen coils (Figure 6-2), the forces on the coil adjacent to a short-circuited coil and due to a current of 8.54 mega-amp turns through each of fifteen coils (Figure 6-3), and the lateral forces resulting from an applied constant vertical field of 5000 gauss (Figure 6-4) were obtained using the computer program PDXFORC. The computer codes PDXNODE and PDXFORC are described in References (3) and (4), respectively, and have subsequently been modified to include both ovals and the constant tension D-shaped coils.

The conductor support structure, the dewar, the shear panels, and the bucking cylinder are assumed to be of steel ($E = 30 \times 10^6$ psi) while the conductor is assumed to be of copper ($E = 17 \times 10^6$ psi). For modeling purposes, the coil finite elements were modeled as parallel

materials resulting in a homogenous isotropic material ($E = 25.29 \times 10^6$) whose properties correspond to a material having a conductor support structure to conductor cross-section area ratio of 1.76 to 1.0. If the conductor support structure was assumed to be of aluminum ($E = 10 \times 10^6$ psi), the homogenous isotropic material would have a modulus of $E = 12.54 \times 10^6$ psi.

The displacement boundary conditions (see Figure 6-1) on a model of one-fourth symmetry for the TF loading condition require the z-direction displacement to be zero on the horizontal midplane, the x-direction displacement to be zero on the vertical midplane, and the x' - direction displacement to be zero on the 11.25 degree plane. For the case where the coil is restrained by the bucking cylinder, the inner leg is unrestrained at the wedge face.

For the vertical field loading condition, the displacement boundary conditions (see Figure 6-1) require the x and y - direction displacements to be zero at the horizontal midplane, the y and z - direction displacements to be zero at the vertical midplane and the y' and z' - direction displacements to be zero for the dewar, the shear panels, and the bucking cylinder at the 11.25 degree wedge plane. The vertical leg of the coil is unrestrained at the wedge plane. These boundary conditions are also valid for a model of one-fourth symmetry.

2.2 FINITE ELEMENT ANALYSIS MODELS

Three different model geometries with different restraint conditions were analyzed. The loading conditions considered were the toroidal field loading and the vertical field loading, but not the fault loading condition.

The first model (computation TF01, see Section 4.1) was the toroidal field loading of the basic D-shaped coil (Figure 6-1) without the dewar or the shear panel lateral support structure. The restraint for the vertical leg was provided by wedging it with its neighbors.

The second model was for a geometry which included the coil, dewar, and shear panels (Figure 6-5); and in which the coil loads were transferred to the dewar by bolts which were

simulated by coupled nodes (Figure 6-6). For the vertical field loading condition (computation EF02, see Section 4-2) the vertical leg was unrestrained at the wedge plane and for the toroidal field loading condition (computation TF02, see Section 4.3) the vertical leg wedged with its neighbor. A combined vertical and toroidal field loading (computation ET02, see Section 4.4) was also performed.

The third series of computations included the vertical field loading (computations EF03 and EF04, see Sections 4.5 and 4.6) and the toroidal field loading (computation TF04, see Section 4.7) and were performed on a geometry which included the coil, dewar, shear panels, and bucking cylinder (Figure 6-7). The coil loads were transferred to the dewar by means of spokes (Figure 6-8). The spokes were modeled as pin jointed three dimensional spar elements with only axial load carrying capabilities. In computation EF03, the vertical leg was restrained laterally by the bucking cylinder. For the toroidal field loading condition, computation TF04, the vertical leg did not wedge into its neighbor but was restrained by the bucking cylinder. The interface elements between the coil and the bucking cylinder were three dimensional gap elements.

In incorporating the bolts into the ANSYS computer code for the second series of computations (EF02, TF02, and TF02) and for the third series of computations (EF03, EF04, and TF04), three different model choices were considered. The first choice would be to model the bolts as three dimensional beam elements whose nodes could be translated and rotated. This would, however, result in incompatible degrees of freedom between the coil elements (whose node points can only be translated in the three coordinate directions) and the beam elements (whose node points can be both rotated and translated in the three coordinate directions). To remove this incompatibility, constraint equations relating the nodal rotations of the beam elements to the bolt length and to the nodal translations of the coil and dewar elements must be developed. This model choice for the bolts was discarded because of the long development time required to obtain the constraint equations. The second model choice for the bolts would be to consider them as three dimensional spars. This model choice would give no bending stiffness for the in-plane loads since pinned joints are in the definition of the spar

elements. This model simulates a flexible coupling between the coils and the dewar. The third model choice for simulating the bolts would be to couple the nodes in the three coordinate directions. This model simulates a perfect or rigid connection between the coils and the dewar. The last two models would bound the first model choice. The model with rigid connections would demonstrate the effect of perfect coupling between the TF coil in-plane loads with the out-of-plane shear panel support structure, while the model with pin joints would decouple the in-plane loads from the out-of-plane support structure. For comparison purposes the perfect connection was assumed for the second TF coil model (computations EF02, TF02, and ET02) and the third TF coil model used the spar elements to simulate the bolts (computations EF03, EF04, and TF04).

2.3 INTERPRETATIONS OF THE FINITE ELEMENT ANALYSIS RESULTS

The finite element analysis results are accurate for the model within the framework of the assumptions made with respect to the materials, loads, and boundary conditions. The scope of the results can be extended through the use of closed form solutions.

The finite element analysis model used herein assumes that the cross-section of the coil is of a homogenous material with a specific modulus ($E = 25.29 \times 10^6$ psi). In actuality, the coil cross-section is a composite of pancakes which are bolted together. Each pancake contains the support structure, the superconductor, insulation, coolant holes, etc. Consequently, the finite element model stress and displacement results for a given material must be scaled using the moduli of the material. The effect of the coil cross-sectional material inhomogeneities, discontinuities, stress concentrations, etc., which the finite element model disregards, must be determined through closed form calculations.

Specifically, the finite element analysis results which are particular to the given model, must be generalized to fit other models.

2.4 CLOSED FORM ANALYSIS METHODS

This section lists a set of equations which can be used in the design of the TF coil. An expression for the constant tension in the D-shaped TF coil is presented in Section 2.4.1. Section 2.4.2 considers the effects of the differential thermal expansions of the various materials on the stresses and strains during cooldown of the coil system. Section 2.4.3 contains an expression for the strain in the conductor while Section 2.4.4 contains an expression for the maximum stress in the conductor support structure due to stress concentrations; both expressions are valid for TF loading only. In Sections 2.4.5 and 2.4.6, shear stresses in the bolts are considered across any cross-section, and in the vertical leg restrained by wedging, respectively. In Section 2.4.7 formulae are presented to determine the inner radius of the bucking cylinder under in-plane loads only.

The nomenclature to be used in conjunction with this section is presented at the beginning of this report.

2.4.1 The Constant Tension in the D-Shaped Coil Due to TF Loading

For the constant tension D-shaped coil shown in the above figure, Reference (1) gives an expression for the radius of curvature at any point as

$$\rho = \frac{R}{S} \left\{ \frac{4\pi F}{\mu_0 I} - \ln \frac{1.284 R}{e S} \right\} / \left(1 + \frac{1}{S} \cos \theta \right) \quad (2.1)$$

where R is the distance along the abscissa (see figure), S the number of coils, μ_0 the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ N/m), F is the constant tension across the cross-section, I is the ampere turns per coil, θ is the angle shown in the figure, and the parameter e depends on the shape of the coil cross-section.

Rearranging terms in equation (2.1), setting $\theta = 0$ and consequently $\rho = \rho_2$ and $R = R_2$, and setting $e \approx 0.573W$ for an equivalent square cross-section where w is the side of the square, one obtains

$$F = \frac{\mu_0 (S I)^2}{4 \pi S} \left(\frac{\rho_2}{R_2} \right) (1 + f) \quad (\text{Newtons}) \quad (2.2)$$

where the correction term

$$f = \frac{1}{S} \left\{ 1 + \frac{1}{(\rho_2/R_2)} \ln \left(\frac{2.241 R_2}{S w} \right) \right\} \quad (2.3)$$

usually ranges from 0.05 to 0.20. The ratio ρ_2/R_2 , if unknown, can be obtained from a graph in Ref. (1) if the value of $H_{\max}/R_2$ is known. The ratio may also be approximated as $\rho_2/R_2 \approx 1.10 H_{\max}/R_2$ (2.4)

The use of equation (2.4) in equations (2.3) and (2.2) results in an error of between 2% and 5% in the computed value of the tension.

2.4.2 The Effect of Differential Thermal Expansions

When the coil system is cooled from room temperature to cryogenic temperatures, thermal stresses and strains are developed in the structural materials. The strain in the material due to the temperature decrease is given by

$$\epsilon = \gamma (T_f - T_o) + \sigma_{th}/E \quad (2.5)$$

where γ is the linear coefficient of thermal expansion, T_f and T_o are the final and initial temperatures, σ_{th} is the thermal stress and E the Young's modulus. In equation (2.5) the first term on the right hand side represents the stress free strain and the second term represents the strain induced in the body to ensure that the total strain ϵ satisfies the compatibility equations. The force developed in the material due to the thermal stress is given by $A \sigma_{th}$, where A is the cross-section area.

Assuming that the support structure and the conductor are in parallel, the strain in the conductor must equal the strain in the support structure, and the sum of the thermally induced

forces in the conductor and the support structure must be zero. Consequently one has

$$\gamma_{SS} (T_f - T_o)_{SS} + \left(\frac{\sigma_{th}}{E} \right)_{SS} = \gamma_c (T_f - T_o)_c + \left(\frac{\sigma_{th}}{E} \right)_c \quad (2.6a)$$

$$(A \sigma_{th})_{SS} + (A \sigma_{th})_c = 0 \quad (2.6b)$$

The simultaneous solution of equations (2.6a) and (2.6b) will yield values for the thermal stresses in the conductor and in the support structure.

$$(\sigma_{th})_{SS} = \frac{\gamma_c (T_f - T_o)_c - \gamma_{SS} (T_f - T_o)_{SS}}{\left[\frac{1}{E_{SS}} + \frac{A_{SS}}{A_c E_c} \right]} \quad (2.7a)$$

$$(\sigma_{th})_c = \frac{\gamma_{SS} (T_f - T_o)_{SS} - \gamma_c (T_f - T_o)_c}{\left[\frac{1}{E_c} + \frac{A_c}{A_{SS} E_{SS}} \right]} \quad (2.7b)$$

The above equations have only treated the insulator as a thin bonding agent to transmit force equilibrium between the conductor and the support structure. Since gaps, delaminations and/or low modulus fillers could invalidate the above modeling, a conservative approach should be used when applying the results. Consequently, in subsequent sections, any added tension in the support structure from the thermal cooldown is considered but any computed beneficial conductor thermal compressive strains from the cooldown are neglected.

2.4.3 The Strain in the Conductor Due to TF Loading

Consider TF loading only. Let the cross-section tension F be distributed among M of the N pancakes and let B be the ratio of the highest stress to the lowest stress across the cross-section (due to bending). Denote the cross-section of the conductor as A_c (of modulus E_c) in each pancake as A_{SS} for the support structure (of modulus E_{SS}), and as A_H for the insulation, helium coolant holes, air spaces, etc., (of modulus E_H). The effective modulus of the cross-section is given by

$$E = \frac{E_c A_c + E_{SS} A_{SS} + E_H A_H}{(A_c + A_{SS} + A_H)} \quad (2.8)$$

and the highest tensile stress in a pancake by

$$\sigma = \frac{B F}{M (A_c + A_{SS} + A_H)} \quad (2.9)$$

The highest tensile stress in the conductor and support structure are given by

$$\sigma_c = E_c \epsilon/E$$

$$\sigma_{SS} = E_{SS} \epsilon/E \quad (2.10)$$

respectively, and the highest strain in the conductor and support structure are given by

$$\epsilon_c = \epsilon_{SS} = B F / M A_c (E_c + A_{SS} E_{SS} / A_c + A_H E_H / A_c) \quad (2.11)$$

2.4.4 Stress Concentration Factors Due to TF Loading

The N laminations across the cross-section of the D-shaped coil are held together by c rows of bolts; d bolts in every row. In Peterson (Ref. 22), the maximum value for the stress concentration factor $\sigma_{\max}/\sigma$ is given as 3.0 for both the cases where a single line of holes or a double line of holes is present in a plate under uniform tensile stress (when the ratio of the hole spacing to the hole diameter is greater than 5.0).

The maximum stress due to stress concentrations in the support structure becomes (using equations (2.7a) and setting $E_H = 0$,

$$\sigma_{\max SS} = 3 \left[\frac{\gamma_c (T_f - T_o)_c - \gamma_{SS} (T_f - T_o)_{SS}}{\left[1/E_{SS} + A_{SS}/A_c E_c \right]} + B F E_{SS}/M A_c (E_c + E_{SS} A_{SS}/A_c) \right] \quad (2.12)$$

where it is assumed that only M of the N pancakes carry the cross-section tension.

2.4.5 Bolt Shear Due to TF Loading

Consider TF loading only. Let M of the N pancakes across the cross-section of the coil carry the total tension F in Q equal amounts (see above figure). The maximum load that can be carried by the bolts in shear is given by $F_{\max} = \frac{\pi}{2} cd MD^2 \tau_{\max}$ (2.13)

where c denotes the number or rows of bolts, d the number of bolts in a row, D the diameter of a bolt, and $\tau_{\max}$ the maximum allowable shear stress in the bolt. If $F_{\max}/F$ is less than the required factor of safety, the bolts are safe in shear.

2.4.6 The Coil Vertical Leg Restrained by Wedging Only

Due to the TF loading, the vertical leg is subjected to a centering force Rb (see figure on page 2-13). The center section of the vertical leg (see figure) is prevented from shearing off due to the shear stress τ developed in each of the c rows of bolts of diameter D spaced a apart, and due to the friction force developed as shown. If α is the wedge angle, the center section will not shear off if the ratio of shear stress in the bolts

$$\tau = \frac{2Rb (1 - \mu \cot \alpha)}{\pi D^2 c (1 + b/a)} \quad (2.14)$$

to the allowable shear stress $\tau_{\max}$ in the bolts is less than the required factor of safety. One notes, from equation (2.14), that if $\mu = \tan \alpha$, the shear stress in the bolts is zero.

2.4.7 The Coil Vertical Leg Restrained by the Bucking Cylinder Due to TF Loading Only

If R is the running load on the vertical leg due to the centering force and b the half length of the vertical leg, the total centering force due to toroidal field loading is $2Rb$. Let the inner and outer radii of the bucking cylinder be r_i and r_o , respectively. The external

$$\text{pressure on the bucking cylinder is } p = 2Rb/A = RS/2 \pi r_o \quad (2.15)$$

where S is the number of TF coils.

For a given outer radius of the bucking cylinder r_o , the inner radius r_i must be determined through the dual considerations of stress analysis and buckling. Let the maximum allowable normal stress in the bucking cylinder be F_{ty}/f_1 , the maximum allowable shear stress be F_{sy}/f_1 , and the pressure p not to exceed p_{cr}/f_2 ; where F_{ty} and F_{sy} are the tensile and shear yield of the material, p_{cr} the buckling pressure, and f_1 and f_2 suitable design factors of safety.

Using the formulae given in Roark (Reference 23) for the maximum stresses in a thick cylinder subjected to an external pressure p , the smaller value of r_i computed from the formulae

$$r_i = r_o \left[1 - \frac{2p}{F_{ty}/f_1} \right]^{1/2} \quad (2.16a)$$

$$r_i = r_o \left[1 - \frac{p}{F_{sy}/f_1} \right]^{1/2} \quad (2.16b)$$

would give the minimum acceptable external radius from stress analysis considerations.

From buckling considerations, the inner radius of the bucking cylinder can be determined from the formula, valid for a thin-walled cylinder with ends held circular given in Roark (Ref. 23)

$$r_i = r_o \left[1 - \left\{ \left[\frac{2bp f_2}{0.807 E r_o} \right]^4 (1 - \nu^2)^3 \right\}^{1/10} \right] \quad (2.16c)$$

where E and ν are the material moduli of the bucking cylinder. The computed value of r_i from equation (2.16c) must satisfy $r_i/r_o \geq 0.9$ (2.16d)

if not, r_i could be calculated from the thick cylinder stability analysis of Felgar. (Reference 24)

The smallest value for the inner radius r_i of the bucking cylinder computed from equations (2.16a, b, c) is to be used.

3.0 SUMMARY

This section contains a summary of the results of the analyses performed on the different D-shaped coil configurations using the analysis methods and models described in Section 2.0. The force computation results are presented in Section 3.1, the toroidal field loading computation results in Section 3.2, the vertical field loading computation results in Section 3.3, and the combined toroidal and vertical field loading computation results in Section 3.4. A set of conclusions and suggestions for some design modifications is presented in Section 3.5. The detailed results of the different analyses are contained in Section 4.0.

3.1 RESULTS OF THE FORCE COMPUTATIONS

Table 6-1 presents the forces on the coil due to the different loading conditions. The toroidal field forces, shown in Figure 6-2, are in-plane; i.e., there are no lateral forces or overturning moments. The forces on the coil, excluding those on the vertical leg, are in equilibrium. The fault condition forces, Figure 6-3, are such that there is no overturning moment. The vertical field forces, Figure 6-4, are all out of plane and result in overturning moments.

3.2 RESULTS OF THE TOROIDAL FIELD LOADING COMPUTATIONS

The results of the finite element and closed form analyses of the toroidal field loading of the basic D-shaped coil (without dewar or shear panel lateral support) are presented in Section 3.2.1. A comparison of the finite element analyses, computations TF01, TF02, and TF04, is made in Section 3.2.2.

3.2.1 The Toroidal Field Loading of the Basic D-Shaped Coil

The toroidal field loading of the D-shaped coil, (computation TF01, Section 4.1), indicates that the coil very closely represents a constant tension shape. The net normal force, Figure 4.1.2, across any cross-section of the coil is computed from the finite element stress and area and has a constant value of about 18.2×10^6 lbs; although the cross-sectional stress distributions, Figure 4.1.3, indicates that bending is present. The ratio of the highest normal stress to the lowest normal stress across the cross-section is less than 1.6 (or the highest stress is 1.3 times greater than the average stress).

The use of equations (2.2) and (2.3) (see Section 2.4.1), yields a tension value across the cross-section of the coil of 18.097×10^6 lbs. Consequently, it is determined that equations (2.2) and (2.3) are valid.

The TF coil displacements (Figure 4.1.1) and stresses (Figures 4.1.4 through 4.1.9) are obtained assuming that the coil cross-section is homogenous with a modulus of $E = 25.29 \times 10^6$ psi.

In actuality the coil cross-section is a composite of several different materials. The stresses in any of the composites can be obtained by appropriate scaling with the modulus of the composite. If the conductor is of copper, the largest magnitude of stress in the copper in a direction normal to the cross-section (Figure 4.1.3) is about 11,000 psi. If the support structure were either of steel or aluminum, the largest normal stress in it would be either 19,600 psi or 13,000 psi, respectively.

3.2.1.1 The Strain in the Conductor

The strain in the conductor due to TF loading can be obtained by using the equations listed in Section 2.4.3. The cross-section areas in each pancake are given by $A_c = 11.775$ sq. in., $A_{SS} = 20.724$ sq. in., and $A_H = 5.769$ sq. in. In the current design, only $M = 20$ pancakes (of the $N = 40$ pancakes) carry the entire cross-section tension of $F = 18.2 \times 10^6$ lbs. between cross-sections of the coil which are separated by a distance equal to the length of the pancakes. If the conductor is of copper ($E_c = 17 \times 10^6$ psi), the support structure of steel ($E_{SS} = 30 \times 10^6$ psi), and setting $M = 20$, $B = 1.3$, and $E_H = 0$, the strain in the copper conductor is obtained from equation (2.11) as 0.144%. If on the other hand, aluminum is the support structure ($E_{SS} = 10 \times 10^6$ psi), the strain in the copper conductor is 0.29%.

By appropriately staggering the pancake segments lengthwise, as indicated in Figure 6-9, one could have as many as $M = 39$ pancake segments carrying the tension across any two cross-sections. In this case, for a copper conductor and a steel support structure, the strain in the conductor is 0.074%. If the support structure is of aluminum, the strain in the copper conductor is 0.149%.

3.2.1.2 Stress Concentration Effects in the Pancake

Stress concentration effects can be determined through the use of the equations listed in Section 2.4.4.

In cooling the coil system from 293K to 4K, the free contraction in steel would be - 0.28%, in aluminum - 0.37%, and in the conductor (assumed to contain 4 parts of copper to 1 part of niobium titanium) - 0.23% (see Reference 21).

In the current design, with $M = 20$ pancakes carrying the cross-section tension of $F = 18.2 \times 10^6$ lbs., equation (2.12) indicates the stresses in a steel support structure could be as high as 138,308 psi and in an aluminum support structure about 108,000 psi (assuming a conductor of copper and niobium titanium). If $M = 39$ pancakes carry the cross-section tension and if the support structure were of steel, equation (2.7a), (2.8), (2.9), and (2.10) give the highest stress in the steel due to TF loading and thermal cooldown as 25,066 psi (instead of the 46,103 psi in the $M = 20$ design), while equation (2.12) gives the maximum stress due to stress concentrations as 75,198 psi (instead of the 138,308 psi in the $M = 20$ design). If the support structure were of aluminum, the highest stress due to TF loading and thermal cooldown would be 21,770 psi (instead of the 35,916 psi in the $M = 20$ design) while the maximum stress due to stress concentrations would be 65,308 psi (instead of the 108,000 psi in the $M = 20$ design).

3.2.1.3 The Feasibility of Using Aluminum as a Conductor Support Material

If the design suggestion for positioning the pancakes as indicated in Figure 6-9 is carried out, i.e., if $M = 39$, and if the support structure is of aluminum, the strain in the superconductor (0.149%) is close to the limiting value of 0.15% and the maximum stress in the support structure (65,308 psi) is close to the tensile yield of 80,000 psi for 7075 aluminum alloy (Ref. 25) (at 20K). Under combined toroidal field and vertical field loading, it is most likely that aluminum cannot be used as a support structure material in the present design of the coil.

Consider TF loading alone and let the support structure be of aluminum. Assume the limiting value for the strain in the conductor be 0.1% and for the stress in the aluminum be 50,000 psi. Assume the ratios $A_{SS}/A_C = 1.76$ and $A_H/A_C = 0.49$ (as in the present design). Using equation (2.11) and setting $M = 39$, one obtains $A_C = 17.534$ sq. in. and $A_{SS} = 30.86$ sq. in. for $E_H = 0$ (as assumed in the analysis for the $M = 20$ design). Using equation (2.12) yields $A_C = 17.91$ sq. in. and $A_{SS} = 31.53$ sq. in. The latter, higher values, for the areas are to be used. Further, one obtains $A_H = 8.776$ sq. in., consequently the cross-sectional area for each pancake is 58.216 sq. in. The total cross-sectional area for the coil becomes (for 40 laminations) 2328.64 sq. in. This represents a 52% increase over the present area.

These values for the area are based on the assumption that 39 pancakes carry the cross-section tension.

If a coil with the suggested cross-sectional area is used, the forces on it will be different from the forces on the coil under consideration; consequently the coil shape, including the cross-section area, should be obtained iteratively.

3.2.1.4 Bolt Shear At Any Cross-Section

The safety of the bolts in shear can be determined through the results of Section 2.4.4.

Assuming that $c = 3$ rows of bolts are used, that $d = 8$ bolts per row are present, that the diameter of the bolts is $D = 0.75$ inches, that the shear allowable in the bolts is

$\tau_{max} = 50,000$ psi, and that $M = 39$ pancakes carry the total tension, equation (2.11) yields

$F_{max} = 41.35 \times 10^6$. Since this is more than two times the cross-section tension of

$F = 18.2 \times 10^6$ lbs, the bolts are determined to be safe in shear.

If only $M = 20$ pancakes carry the entire cross-section tension, one obtains $F_{max}/F = 1.17$.

The factor of safety is, consequently, greatly reduced when compared to the case when $M = 39$ pancakes carry the cross-section tension.

3.2.1.5 Bolt Shear Along Vertical Leg

If the TF coil vertical leg is assumed to be restrained by wedging only under TF loading conditions, the model of Section 2.4.5 may be applied. For $S = 16$ coils in the machine, one has $\alpha = 11.25^\circ$. Assuming $c = 3$ rows of bolts of diameter $D = 0.75$ inches spaced $a = 4.5$ inches apart, and setting $b = 147$ inches (Figure 6-1) and $R = 215 \times 10^3$ lb/inch, (Figure 6-2), equation 2.14 yields the shear stress in the bolts as $\tau = 179,666$ psi if the coefficient of friction is taken as $\mu = 0.1$. If the bolt shear is to be restricted to 100,000 psi, bolts of diameter $D = 1.0$ inch are required, whereas if τ is limited to 50,000 psi, bolts of diameter $D = 1.42$ inches are required. On the other hand, if the coefficient of friction $\mu = 0$ and if τ is assumed to be 100,000 psi maximum, bolts of diameter $D = 1.43$ inches are required; with the bolt spacing maintained at $a = 4.5$ inches.

3.2.1.6 Dimensions of the Bucking Cylinder

If the TF coil inner leg is assumed to be restrained by the bucking cylinder, the inner radius of the bucking cylinder can be estimated with the models of Section 2.4.7. For the low field (8 Tesla) design, setting the running load on the vertical leg $R = 215 \times 10^3$ lb/inch (Figure 6-2), the number of coils $S = 16$, the outer radius of the bucking cylinder $r_o = 106$ inches (Figure 6-1), equation (2.13) yields a pressure of $p = 5165$ psi on the exterior of the bucking cylinder.

Assuming that the material of the bucking cylinder is Nitronic 33 with tensile yield $F_{ty} = 118,000$ psi and shear yield $F_{sy} = 59,000$ psi, and a factor of safety $f_1 = 2$, the inner radius of the bucking cylinder as obtained from equations (2.16a) and (2.16b) is $r_i = 96.3$ inches. Assuming that Nitronic 33 has moduli $E = 30 \times 10^6$ psi and $\nu = 0.3$, and using a factor of safety $f_2 = 5$, the inner radius of the bucking cylinder as obtained from equation (2.16c) is $r_i = 96.0$ inches. Using this latter value for r_i , one has $r_i/r_o > 0.9$. Consequently equation (2.16d) is satisfied and therefore a wall thickness of 10 inches is appropriate for the bucking cylinder.

3.2.2 Comparison of the Results of the Different Toroidal Field Loading Computations

A summary of the pertinent displacement, stress, and load results of the finite element analysis computations TF01, TF02, and TF04 is given in Table 6-2. For computation TF01, the detailed displacement results are shown in Figure 4.1.1, while the stress results are documented in Figures 4.1.3 through 4.1.9. For computation TF02, the displacement results are shown in Figure 4.3.1, while the stress results are shown in Figures 4.3.2 through 4.3.8. For computation TF04, the displacements are shown in Figure 4.7.1 and the stress results are presented in Figures 4.7.2 through 4.7.6. The results for computation TF01 are for a particular coil with a specific Young's modulus but may be scaled to apply to a coil with a composite material cross-section. On the other hand, the results for computation TF02 and TF04 cannot be scaled to a coil system which has different materials from that analyzed, since the analyzed coil systems themselves contain different materials.

Table 6-2 indicates that computation TF02 which rigidly coupled the in-plane forces with the lateral support structure results in higher stresses but smaller coil displacements when compared to computation TF04 which decoupled the in-plane forces from the lateral support structure. The shear load in the bolt simulations is high for the case of the rigid coupling and clearly indicates that the flexible coupling is preferable to the rigid coupling.

Computations TF01 and TF04 provide a valid comparison between the effects of restraining the vertical leg of the coil by wedging versus bucking, respectively. The displacements and stresses in computation TF04 (where the inner leg is restrained by the bucking cylinder) are slightly lower than in computation TF01 (where the inner leg is restrained by wedging); but this can be attributed to the additional system structures used in computation TF04 in comparison with that used in computation TF01 (see Figures 6-1 and 6-7).

3.3 RESULTS OF THE VERTICAL FIELD LOADING COMPUTATIONS

A summary of the pertinent displacement, stress, and load results of the finite element analysis computations EF02, EF03, and EF04 is given in Table 6-3. For computation EF02, the detailed lateral displacement and slope results are given in Figure 4.2.1, while the stress results are shown in Figures 4.2.2 through 4.2.10. For computation EF03, the pertinent displacements and slopes are shown in Figure 4.5.1, while the stress results are documented in Figures 4.5.2 through 4.5.13. For computation EF04, the lateral displacements and slopes are shown in Figure 4.6.1, the shear panel reactions are shown in Figures 4.6.2 and 4.6.3, and the stresses are shown in Figures 4.6.4 through 4.6.15. The results of all the above three computations (EF02, EF03, and EF04) for a particular coil system with specific material properties assigned to the substructures within the system; consequently the finite element analysis results cannot be scaled to a coil system whose substructures are materially different.

In Table 6-3, the higher slope results indicated for computation EF02 in comparison with computations EF03 and EF04, are attributed to the fact that the shear panel lateral support structure for the configuration in computation EF02 is smaller (Figure 6-5) than for computations EF03 and EF04 (Figure 6-7). Although a limiting value for the coil slope has not been established, the coil slopes obtained in computation EF02 are large compared to those obtained in computations EF03 and EF04. Figures (4.6.2) and (4.6.3) indicate that the shear force distribution along the shear panels is directed approximately tangential to the coil near the location of the horizontal mid-plane and near the location of maximum height, and is directed approximately normal to the coil over the central portion of the shear panels.

A comparison of the stresses as obtained in the three computations (Table 6-3), shows that they are higher in computation EF02 than in computations EF03 and EF04. This is attributed to the fact that a rigid coupling was used between the coil and dewar in computation EF02 while the coil was coupled to the dewar in a flexible manner in computations EF03 and EF04. Although the axial load in the bolt simulations are higher for computations EF03 and EF04 in comparison with EF02; they are reasonable since the high value of 167,648 lbs. (Table 6-3) corresponds to a stress of 53,364 psi in a 2 inch diameter spoke (spokes of materials with a

tensile yield of 118,000 psi could be used.

The results for computations EF03 and EF04 (Table 6-3) provide a valid comparison between the effects of keying with the bucking cylinder (computation EF04) and no keying (computation EF03). The lateral slopes and stresses for the configuration with keying to the bucking cylinder are slightly lower than for the configuration without keying to the bucking cylinder.

3.4 RESULTS OF THE COMBINED TOROIDAL FIELD AND VERTICAL FIELD LOADING COMPUTATIONS

The results of computations TF01 can be combined with those of computation EF03 to approximately determine the effect of the combined loading on the coil system shown in Figure 6-7 for the following reasons: first the bucking cylinder is not used as a means of restraint for the vertical leg in either of these computations, and secondly the configuration for both of these computations can be interpreted as representing a decoupling of the in-plane forces from the lateral support structure (had a TF loading computation been performed on the coil system of computation EF03 with wedging as a means of vertical leg restraint, the results would be close to those of computation TF01). A separate computation which represents the combination of computations EF02 and TF02 was performed (computation ET02) and its results which are shown in Figures 4.4.1 through 4.4.13 of Section 4.4 represent the effect of the combined loading on the coil system of Figure 6-5. The results of computations TF04 and EF04 can be combined to determine the effect of the combined loading on the coil system of Figure 6-7 where the bucking cylinder is used as a means of restraining the vertical leg.

A summary of the approximate results of the combined loading is shown in Table 6-4 for the different computations. The maximum values for the stresses are not listed for comparison in Table 6-4 since these are difficult to establish for the combined computations TF01 and EF03 and for TF04 and EF04. In a relative comparison between rigid coupling (ET02) and flexible coupling (TF01 and EF03, and TF04 and EF04) of the coil and the lateral support

structure, the in-plane displacements (row 2, Table 6-4) and the axial load in the bolt simulations (row 5, Table 6-4) are lower for rigid coupling while the lateral slopes (rows 3 and 4, Table 6-4) and the shear loads in the bolt simulations (row 6, Table 6-4) are much higher for rigid coupling. The shear load of 990,000 lbs. corresponds to a shear stress of 315,127 psi in a two inch diameter bolt. The rigid coupling also results in high y-directional normal stresses (94,910 psi) in the dewar as shown in Figure (4.4.9). A relative comparison between the merits of restraining the coil vertical leg by wedging (combination of computations TF01 and EF03) versus using the bucking cylinder (combination of computations TF04 and EF04) can be made from the results in Table 6-4. The in-plane displacements, lateral slopes, and loads in the bolt simulations are slightly lower when the bucking cylinder is used than when wedging is used to restrain the vertical leg.

3.5 CONCLUSIONS/RECOMMENDATIONS

Certain conclusions and recommendations are made in this section on the basis of the various analyses.

- The D-shaped coil used in this study closely results in a constant tension of about 18.2×10^6 lbs. across all cross-sections of the coil due to the toroidal field. However, bending is present across the cross-sections of the coil and the ratio of the highest normal stress to the lowest normal stress is about 1.6 (or the highest stress is 1.3 times greater than the average stress).

The equation for the tension across the cross-section, listed in Section 2.4.1, is judged to be valid.

- Based on the results of Section 3.2.1.1 which considers the strain in the superconductor and Section 3.2.1.2 which considers stress concentrations effects in the conductor support structure, the $M = 20$ method of positioning the pancakes, lengthwise, must be altered according to the design suggestion in Figure 6-9. If N pancakes are present across the

cross-section, a maximum of $(N-1)$ pancakes can be made to carry the cross-section tension (instead of the $N/2$) pancakes in the $M = 20$ design).

- Aluminum can be used as a conductor support structural material if the present cross-section area is increased 52%. Under TF loading, this would result in a superconductor strain of 0.1% and an aluminum support structure stress of 50,000 psi due to stress concentrations. These results are obtained assuming that 39 pancakes carry the cross-section tension (instead of the $M = 20$ pancake design).
- With steel as the support structure material and the $M = 20$ design, the strain in the superconductor is 0.144% due to TF loading alone. With 39 pancakes carrying the cross-section area, the strain in the superconductor is 0.074% due to TF loading alone.
- With steel as the support structure material and the $M = 20$ design, the maximum stress in the steel due to stress concentrations is 138,308 psi. With 39 pancakes carrying the cross-section tension and no increase in cross-section area, this reduces to 75,198 psi. This considers TF loading and thermal stresses only.
- With 39 pancakes carrying the cross-section tension, the bolts are safe in shear whereas with 20 pancakes the bolts are marginally safe in shear due to TF loading only.
- When the vertical leg of the coil is restrained by wedging under TF loading alone, the bolts along the vertical leg (assuming 3 rows of bolts of diameter 0.75 inches spaced 4.5 inches apart) have a shear stress of about 180,000 psi if the coefficient of friction between pancakes is 0.1. With 1.0 inch diameter bolts the shear stress is 100,000 psi, and with 1.42 inch diameter bolts the shear stress is 50,000 psi. If the coefficient of friction is zero, bolts of 1.43 inches diameter are required to limit the bolt shear stress to 100,000 psi.

- A bucking cylinder of 10 inches wall thickness is required to restrain the coil vertical leg due to the 8 Tesla toroidal field loading.
- To maintain the coil lateral slopes within what are assumed to be acceptable limits, the circumferential shear panel lateral support structure shown in Figure 6-5 may be insufficient, while the shear panels shown in Figure 6-7 are more adequate. Since the shear panel support structure shown in Figure 6-7 excludes the space for the neutral beam window, a compromise may be necessary between requirements for the neutral beam and structural requirements.

The shear force distribution in the shear panels shown in Figures 4.6.2 and 4.6.3 indicate that the shear force direction is tangential to the coil near the location of the horizontal midplane and near the location of maximum vertical height, and is normal to the coil in between these two locations. The optimum shapes and locations for the shear panels would probably be as shown in Figure 6-10. However, care must be exercised, since prior experience, References (18) and (19), indicates that discontinuous shear panels may give rise to unduly high stresses in the dewar.

Reference (20) indicates that the shear panel design might be required such that it transmits compression only along the machine circumferential direction. This is because of the fact that under the fault condition, the two coils adjacent to the short-circuited coil may have such high tensile forces in their shear panels that a mechanical connection cannot be designed to hold such loads. If this is the case, two probable structural solutions are to either design a tensile slip joint in the shear panels, or to include a joint designed to fail in a controlled manner during the fault condition.

- When the coil is rigidly coupled to the dewar, the stresses in the dewar and load transfer elements are excessive. It is therefore suggested that the coil be flexibly coupled (i.e., the load transfer elements to be spokes which carry axial load only) to the dewar; the stresses in this case are more reasonable.

- The combined in-plane and out-of-plane force analysis of the coil indicates that the displacements (both in-plane and out-of-plane) and stresses in the coil are slightly lower when the vertical leg of the coil is restrained by the bucking cylinder than when the vertical leg is restrained by wedging. Since no substantial advantages can be seen, a very definite case for using the bucking cylinder as a restraining device instead of wedging cannot be made from structural considerations only. The design of the keys and the prevention of eddy current effects could pose substantial problems in the design of a bucking cylinder. Alternatively, if wedging is used as the means of restraint, care must be exercised to ensure that the pancake segments in the vertical leg do not shear off due to the in-plane forces. For a higher field design, a combined restraint of wedging and bucking cylinder may be more appropriate.
- A structural analysis of the TF coils, during the fault condition, must be performed because this loading condition will probably govern the design of the shear panel lateral support structure to a greater extent than the vertical field loading condition. The fault load condition analysis, unlike the toroidal field loading and the vertical field loading, cannot be performed on a single coil since the loading on all the coils is not the same.

4.0 COMPUTATIONS

This section is an Appendix of detailed results for each of the different computations.

The pertinent results for loads, displacements, and stresses are documented.

4.1 COMPUTATION TF01 (Reference 11)

Loading: Toroidal Field

Geometry: Basic D-shaped coil with trapezoidal cross-section.

Properties: Coil cross-section is homogenous with $E = 25.29 \times 10^6$ psi and $\nu = 0.3$. Properties based on a steel ($E = 30 \times 10^6$ psi) to conductor ($E = 17 \times 10^6$ psi) area ratio of 1.76 to 1.0.

Conditions: Vertical coil of leg wedges with its neighbor.

Figure 4.1.1. Computation TF01. Displacements in the YZ Plane. Viewing Plane $X = 0$.

Figure 4.1.2. Computation TF01. Normal Reactions at Different Coil Cross-sections Based on the Computed Stress.

↓ X

10665	12420	14223	16125
10912	12698	14471	16308

→ Y

LOCATION: HORIZONTAL
MIDPLANE, OUTER LEG
Z-DIRECTION NORMAL
STRESS

↓ X

15691	13867	12371	11159
15761	13996	12501	11239

→ Z

LOCATION: $Z = Z_{MAX}$
Y-DIRECTION
NORMAL STRESS

↓ X

13582	13324	13091	13536
14742	13595	12906	12028

→ Y

LOCATION: HORIZONTAL
MIDPLANE, INNER LEG
Z-DIRECTION NORMAL
STRESS

↓ X

15391	14949	14911	15635
13429	11272	10622	10629

→ Y

LOCATION: START OF
VERTICAL LEG
Z-DIRECTION NORMAL
STRESS

$$\text{CONDUCTOR STRESS} = \frac{E_{\text{CONDUCTOR}}}{25.29 \times 10^6} \times (\text{PRINTOUT STRESS})$$

$$\text{CASING STRESS} = \frac{E_{\text{CASING}}}{25.29 \times 10^6} \times (\text{PRINTOUT STRESS})$$

Figure 4.1.3. Computation TF01. Normal Stresses (psi) at
Different Coil Cross Sections.

$$\text{CONDUCTOR STRESS} = \left(\frac{E_{\text{CONDUCTOR}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

$$\text{CASING STRESS} = \left(\frac{E_{\text{CASING}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

Figure 4.1.4. Computation TF01. The X-Direction Normal Stress (psi). Viewing Plane X = 6.4986 in.

$$\text{CONDUCTOR STRESS} = \left(\frac{E_{\text{CONDUCTOR}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

$$\text{CASING STRESS} = \left(\frac{E_{\text{CASING}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

Figure 4.1.5. Computation TF01. The Y-Direction Normal Stress (psi). Viewing Plane X = 6.4986 in.

$$\text{CONDUCTOR STRESS} = \left(\frac{E_{\text{CONDUCTOR}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

$$\text{CASING STRESS} = \left(\frac{E_{\text{CASING}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

Figure 4.1.6. Computation TF01. The Z-Direction Normal Stress (psi). Viewing Plane X = 6.4986 in.

$$\text{CONDUCTOR STRESS} = \left(\frac{E_{\text{CONDUCTOR}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

$$\text{CASING STRESS} = \left(\frac{E_{\text{CASING}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

Figure 4.1.7. Computation TF01. The XY Shear Stress (psi).
Viewing Plane X = 6.4986 in.

$$\text{CONDUCTOR STRESS} = \left(\frac{E_{\text{CONDUCTOR}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

$$\text{CASING STRESS} = \left(\frac{E_{\text{CASING}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

Figure 4.1.8. Computation TF01. The YZ Shear Stress (psi).
Viewing Plane X = 6.4986 in.

$$\text{CONDUCTOR STRESS} = \left(\frac{E_{\text{CONDUCTOR}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

$$\text{CASING STRESS} = \left(\frac{E_{\text{CASING}}}{25.29 \times 10^6} \right) \times (\text{PRINTED STRESS})$$

Figure 4.1.9. Computation TF01. The XZ Shear Stress (psi).
Viewing Plane X = 6.4986 in.

4.2 COMPUTATION EF02 (Reference 12)

Loading: Vertical field

Geometry: Coil with dewar (located along $0 \leq \theta \leq 107.1^\circ$) and shear panels (located along $45^\circ \leq \theta \leq 90^\circ$).

Properties: $E_{\text{COIL}} = 25.29 \times 10^6$, $E_{\text{DEWAR}} = E_{\text{PANELS}} = 30 \times 10^6$ psi;
 $\nu = 0.3$ (everywhere)

Conditions: Load transferred from coil to dewar by coupled nodes. Vertical leg unrestrained at wedge plane.

DEFINE:

$$\theta = \arctan \left[\frac{z}{(y - y_0)} \right]$$

$$\phi = \arctan \left[\frac{(y_0 - y)}{(z - z_0)} \right] + \frac{\pi}{2}$$

$$0 \leq \xi \leq z_0, \text{ for } y < y_0$$

$$y_0 = 247.235 \text{ in.}$$

$$z_0 = 147.126 \text{ in.}$$

LOCATION	NODE	y (inch)	Z (inch)	UX (inch)	slope (UX/Z)
$\theta = 4.5^\circ$	111/112	467.19	17.466	-0.175332	10.038×10^{-3}
$\theta = 11.3^\circ$	261/262	464.50	43.212	-0.429194	9.932
$\theta = 17.8^\circ$	411/412	459.58	68.335	-0.665531	9.739
$\theta = 26.5^\circ$	611/612	449.64	100.69	-0.941039	9.346
$\theta = 34.9^\circ$	811/812	435.89	131.41	-1.156095	8.798
$\theta = 47.1^\circ$	1111/1112	408.26	173.41	-1.33352	7.690
$\theta = 58.9^\circ$	1411/1412	372.83	208.62	-1.335745	6.402
$\theta = 70.3^\circ$	1711/1712	331.09	234.73	-1.230145	5.241
$\theta = 84.8^\circ$	2111/2112	270.19	252.40	-1.024135	4.058
$\theta = 90.0^\circ$	2261/2262	247.24	253.78	-0.944191	3.721
$\phi = 94.2^\circ$	2311/2312	239.47	253.58	-0.9172475	3.617
$\phi = 110.3^\circ$	2511/2512	209.49	248.99	-0.812619	3.264
$\phi = 133.2^\circ$	2811/2812	168.58	231.00	-0.664396	2.876
$\phi = 154.4^\circ$	3111/3112	136.72	200.00	-0.5331025	2.666
$\phi = 167.7^\circ$	3311/3312	124.14	174.03	-0.4549985	2.614
$\phi = 180.0^\circ$	3511/3512	120.04	147.126	-0.3883525	2.639
$\xi = 110.344$	3761/3762		110.344	-0.29923	2.712
$\xi = 73.563$	4011/4012		73.563	-0.2032765	2.763
$\xi = 36.781$	4261/4262		36.781	-0.1027755	2.794
$\xi = 7.356$	4461/4462		7.356	-0.02062785	2.804

Figure 4.2.1. Computation EF02. The X-Direction Displacement and the Lateral Slope from the YZ Plane.

Figure 4.2.2. Computation EF02. Normal Stresses (psi) at Different Coil Cross-Sections.

Figure 4.2.3. Computation EF02. Stresses (psi) at Different Coil Cross-Sections.

Figure 4.2.4. Computation EF02. The Stresses (psi) in Some Finite Elements of High Stress.

ELEM***	SXX	SYX	SZZ	SXY	SYZ	SZX	S1	S2	S3	τ_{MAX}
401	-38720	-44398	-71599	7284	42701	-23746	-10247	-33916	-110554	50154
402	- 6340	-41701	-41747	11110	29418	- 3616	- 2033	-14969	- 72785	35376
406	-39300	-35556	-51011	20452	33169	-12247	- 6487	-31583	- 87796	40654
410*	- 2238	- 8678	-14538	1971	12069	- 1862	868	- 1969	- 24354	12611
425**	-67002	-12125	-16611	18230	14471	-21681	277	-13903	- 82112	41195
426**	-68598	- 9549	-18042	15341	9651	-19409	- 3115	-13434	- 79640	38262
427	-39009	-19206	-26566	- 4388	27111	-15733	8513	-37249	- 56015	32264
428	- 4142	-39192	-11354	10714	24365	339	6328	- 6038	- 54979	30654
432	-49277	-10528	-24851	14061	20843	- 555	6628	-35364	- 55919	31274
436*	- 2563	- 8635	-13488	1988	11782	- 1970	1020	- 2279	- 23426	12223
1228	2623	-23699	17745	3781	7348	- 5269	20219	2178	- 25729	22974
1229	1050	-78023	7719	14018	13909	- 5034	10945	2581	- 82779	46862
1230	13004	-59069	-11578	21648	-13233	7855	19576	- 8290	- 68929	44253

*CONDUCTOR ELEMENT

**PANEL ELEMENT

***CROSS-RELATE LOCATION OF ELEMENTS WITH FIGURE 4.2.3

Figure 4.15. Computation EF02. The X-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.2.6. Computation EF02. The Y-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.2.7. Computation EF02. The Z-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.2.8. Computation EF02. The XY Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.2.9. Computation EF02. The YZ Shear Stress (psi).
Viewing Plane X = 6.4986 in.

Figure 4.2.10. Computation EF02. The XZ Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

4.3 COMPUTATION TF02 (Reference 13)

Loading: Toroidal field

Geometry: Coil with dewar (located along $0 \leq \theta \leq 107.1^\circ$) and shear panels (located along $45^\circ \leq \theta \leq 90^\circ$).

Properties: $E_{\text{COIL}} = 25.29 \times 10^6$ psi, $E_{\text{DEWAR}} = E_{\text{PANELS}} = 30 \times 10^6$ psi,
 $\nu = 0.3$ (everywhere).

Conditions: Load transferred from coil to dewar by coupled nodes. Vertical leg of coil wedges with its neighbor.

VERTICAL DIAMETER EXPANSION = 0.241852
HORIZONTAL DIAMETER EXPANSION = 0.263881

Figure 4.3.1. Computation TF02. Displacements in the YZ Plane. Viewing Plane $X = 0$.

Figure 4.3.2. Computation TF02. Normal Stresses (psi) at Different Coil Cross-Sections.

Figure 4.3.3. Computation TF02. The X-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.3.5. Computation TF02. The Z-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.3.6. Computation TF02. The XY Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.3.7. Computation TF02. The YZ Shear Stress (psi).
Viewing Plane X = 6.4986 in.

Figure 4.3.8. Computation TF02. The XZ Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

4.4 COMPUTATION ET02 (Reference 14)

Loading: Combined vertical field and toroidal field

Geometry: Coil with dewar (located along $(0 \leq \theta \leq 107.1^\circ)$) and shear panels (located along $45^\circ \leq \theta \leq 90^\circ$)

Properties: $E_{\text{COIL}} = 25.29 \times 10^6 \text{ psi}$, $E_{\text{DEWAR}} = E_{\text{PANELS}} = 30 \times 10^6 \text{ psi}$,
 $\nu = 0.3$ (everywhere)

Conditions: Load transferred from coil to dewar by coupled nodes. Under vertical field loading the vertical leg of the coil is unrestrained at the wedge plane. Under toroidal field loading the vertical leg of the coil wedges with its neighbor.

TOROIDAL FIELD FORCES PLUS VERTICAL FIELD FORCES

LOCATION	AXIAL FORCE (lbs)	SHEAR FORCE (lbs)
1	19441	240836
2	-85999	339865
3	-77564	562088
4	-78555	349369
5	-115132	475618
6	-100601	991298

TOROIDAL FIELD FORCES MINUS VERTICAL FIELD FORCES

LOCATION*	AXIAL FORCE (lbs)	SHEAR FORCE (lbs)
7	34470	313633
8	69215	272932
3	89368	350086
9	42293	523761
5	119810	526635
6	88595	788453

*Lower Half of Coil (Negative Z)

Figure 4.4.1. Computation ET02. The Reactions on Some Selected Node Points Due to the Load Transfer from the Coil to the Dewar.

Figure 4.4.2. Computation ET02. The X-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.4.3. Computation ET02. The Y-Direction Normal Stress (psi). Viewing Plane X = 6.4986 in.

Figure 4.4.4. Computation ET02. The Z-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.4.5. Computation ET02. The XY Shear Stress (psi).
Viewing Plane X = 6.4986 in.

Figure 4.4.6. Computation ET02. The YZ Shear Stress (psi).
Viewing Plane X = 6.4986 in.

Figure 4.4.7. Computation ET02. The XZ Shear Stress (psi).
Viewing Plane X = 6.4986 in.

Figure 4.4.8. Computation ET02. The X-Direction Normal Stress (psi). Viewing Plane X = 31.954 in.

Figure 4.4.9. Computation ET02. The Y-Direction Normal Stress (psi). Viewing Plane $X = 31.954$ in.

Figure 4.4.10. Computation ET02. The Z-Direction Normal Stress (psi). Viewing Plane X = 31.954 in.

Figure 4.4.11. Computation ET02. The XY Shear Stress (psi).
Viewing Plane X = 31.954 in.

Figure 4.4.12. Computation ET02. The YZ Shear Stress (psi).
Viewing Plane X = 31.954 in.

Figure 4.4.13. Computation ET02. The XZ Shear Stress (psi).
Viewing Plane X = 31.954 in.

4.5 COMPUTATION EF03 (Reference 15)

Loading: Vertical field

Geometry: Coil with dewar (located along $0 \leq \theta \leq 107.1^\circ$, the outer diameter of dewar is thereafter maintained at $z = \text{constant}$ to $y = 0$ while the inner diameter of dewar remains parallel to the inner diameter of the coil), shear panels (located along $0 \leq \theta \leq 98.6^\circ$), and bucking cylinder (parallel to the vertical leg).

Properties: $E_{\text{COIL}} = 25.29 \times 10^6 \text{ psi}$, $E_{\text{DEWAR}} = E_{\text{PANELS}} = E_{\text{SPOKES}} =$
 $E_{\text{CYLINDER}} = 30 \times 10^6 \text{ psi}$, $\nu = 0.3$ (everywhere)

Conditions: Load transferred from coil to dewar by axial load carrying spokes. The vertical leg of the coil is unrestrained at the wedge plane.

DEFINE:

$$\theta = \arctan [Z/y - y_0]$$

$$\phi = \arctan \left[\frac{(y_0 - y)}{(Z - z_0)} \right] + \frac{\pi}{2}$$

$$0 \leq \xi \leq z_0; \text{ for } y < y_0$$

$$y_0 = 247.235 \text{ in.}$$

$$z_0 = 147.126 \text{ in.}$$

LOCATION	NODE	y (inch)	z (inch)	UX (inch)	slope (UX/Z)
$\theta = 4.5^\circ$	111/112	467.19	17.466	-0.0178821	1.024×10^{-3}
$\theta = 11.3^\circ$	261/262	464.50	43.212	-0.0418665	1.022
$\theta = 17.8^\circ$	411/412	459.58	68.335	-0.0697303	1.020
$\theta = 26.5^\circ$	611/612	449.64	100.69	-0.102314	1.016
$\theta = 34.9^\circ$	811/812	435.89	131.41	-0.1327965	1.011
$\theta = 47.1^\circ$	1111/1112	408.26	173.41	-0.1734465	1.000
$\theta = 58.9^\circ$	1411/1412	372.83	208.62	-0.2064845	0.990
$\theta = 70.3^\circ$	1711/1712	331.09	234.73	-0.2308525	0.983
$\theta = 84.8^\circ$	2111/2112	270.19	252.40	-0.25064	0.993
$\theta = 90.0^\circ$	2261/2262	247.24	253.78	-0.255083	1.005
$\phi = 94.2^\circ$	2311/2312	259.47	253.58	-0.256263	1.011
$\phi = 110.3^\circ$	2511/2512	209.49	248.49	-0.2584845	1.038
$\phi = 133.2^\circ$	2811/2812	168.58	231.00	-0.249569	1.080
$\phi = 154.4^\circ$	3111/3112	136.72	200.00	-0.2162165	1.081
$\phi = 167.7^\circ$	3311/3312	124.14	174.03	-0.182765	1.050
$\phi = 180.0^\circ$	3511/3512	120.04	147.126	-0.151326	1.029
$\xi = 110.344$	3761/3762		110.344	-0.1131075	1.025
$\xi = 73.563$	4011/4012		73.563	-0.0752896	1.023
$\xi = 36.781$	4261/4262		36.781	-0.0376511	1.024
$\xi = 7.356$	4461/4462		7.356	-0.0075364	1.024

Figure 4.5.1. Computation EF03. The X-Direction Displacement and the Lateral Slope from the YZ Plane

Figure 4.5.2. Computation EF03. The X-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.5.3. Computation EF03. The Y-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.5.4. Computation EF03. The Z-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.5.5. Computation EF03. The XY Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.5.6. Computation EF03. The YZ Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.5.7. Computation EF03. The XZ Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.5.8. Computation EF03. The X-Direction Normal Stress (psi). Viewing Plane $X = 31.954$ in.

Figure 4.5.9. Computation EF03. The Y-Direction Normal Stress (psi). Viewing Plane $X = 31.954$ in.

Figure 4.5.10. Computation EF03. The Z-Direction Normal Stress (psi). Viewing Plane X = 31.954 in.

Figure 4.5.11. Computation EF03. The XY Shear Stress (psi).
Viewing Plane X = 31.954 in.

Figure 4.5.12. Computation EF03. The YZ Shear Stress (psi).
Viewing Plane X = 31.954 in.

Figure 4.5.13. Computation EF03. The ZX Shear Stress (psi).
Viewing Plane $X = 31.954$ in.

4.6 COMPUTATION EF04 (Reference 16)

Loading: Vertical field

Geometry: Coil with dewar (located along $0 \leq \theta \leq 107.1^\circ$, the outer diameter of dewar is thereafter maintained at $z = \text{constant}$ to $y = 0$ while the inner diameter of dewar remains parallel to the inner diameter of the coil), shear panels (located along $0 \leq \theta \leq 98.6^\circ$), and bucking cylinder (parallel to the vertical leg)

Properties: $E_{\text{COIL}} = 25.29 \times 10^6 \text{ psi}$, $E_{\text{DEWAR}} = E_{\text{PANELS}} = E_{\text{SPOKES}}$
 $E_{\text{CYLINDER}} = 30 \times 10^6 \text{ psi}$, $\nu = 0.3$ (everywhere)

Conditions: Load transferred from coil to dewar by axial load carrying spokes. The vertical leg of the coil is restrained by the bucking cylinder.

DEFINE:

$$\theta = \arctan [Z/(y - y_0)]$$

$$\phi = \arctan \frac{(y_0 - y)}{(Z - Z_0)} + \frac{\pi}{2}$$

$$0 \leq \xi \leq Z_0; \text{ for } y < y_0$$

$$y_0 = 247.235 \text{ in.}$$

$$Z_0 = 147.126 \text{ in.}$$

LOCATION	NODE	y (inch)	Z (inch)	UX (inch)	slope (UX/Z)
$\theta = 4.5^\circ$	111/112	467.19	17.466	-0.0174314	0.998×10^{-3}
$\theta = 11.3^\circ$	261/262	464.50	43.212	-0.0430845	0.997
$\theta = 17.8^\circ$	411/412	459.58	68.335	-0.0680221	0.995
$\theta = 26.5^\circ$	611/612	449.64	100.69	-0.09988795	0.992
$\theta = 34.9^\circ$	811/812	435.89	131.41	-0.1297495	0.987
$\theta = 47.1^\circ$	1111/1112	408.26	173.41	-0.169494	0.977
$\theta = 58.9^\circ$	1411/1412	372.83	208.62	-0.201041	0.964
$\theta = 70.3^\circ$	1711/1712	331.09	234.73	-0.2219955	0.946
$\theta = 84.8^\circ$	2111/2112	270.19	252.40	-0.231019	0.916
$\theta = 90.0^\circ$	2261/2262	247.24	253.78	-0.229078	0.903
$\phi = 94.2^\circ$	2311/2312	239.47	253.58	-0.2277175	0.898
$\phi = 110.3^\circ$	2511/2512	209.49	248.99	-0.218273	0.877
$\phi = 132.2^\circ$	2811/2812	168.58	231.00	-0.1895535	0.821
$\phi = 154.4^\circ$	3111/3112	136.72	200.00	-0.14119	0.706
$\phi = 167.7^\circ$	3311/3312	124.14	174.03	-0.104445	0.600
$\phi = 180.0^\circ$	3511/3512	120.04	147.126	-0.0745473	0.507
$\xi = 110.344$	3761/3762		110.344	-0.0478956	0.434
$\xi = 73.563$	4011/4012		73.563	-0.029347	0.398
$\xi = 36.781$	4261/4262		36.781	-0.014002	0.381
$\xi = 7.356$	4461/4462		7.356	-0.0027533	0.374

Figure 4.6.1. Computation EF04. The X-Direction Displacement and the Lateral Slope from the YZ Plane.

Figure 4.6.2. Computation EF04. The Shear Panel Reactions Per Layer (KIPS).

Figure 4.6.3. Computation EF04. The Inner and Outer Shear Panel Reactions Per Layer (KIPS).

Figure 4.6.4. Computation EF04. The X-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.6.5. Computation EF04. The Y-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.6.6. Computation EF04. The Z-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.6.7. Computation EF04. The XY Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.6.8. Computation EF04. The YZ Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.6.9. Computation EF04. The XZ Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.6.10. Computation EF04. The X-Direction Normal Stress (psi). Viewing Plane $X = 31.954$ in.

Figure 4.6.11. Computation EF04. The Y-Direction Normal Stress (psi). Viewing Plane $X = 31.954$ in.

Figure 4.6.12. Computation EF04. The Z-Direction Normal Stress (psi). Viewing Plane $X = 31.954$ in.

Figure 4.6.13. Computation EF04. The XY Shear Stress (psi).
Viewing Plane X = 31.954 in.

Figure 4.6.14. Computation EF04. The YZ Shear Stress (psi).
Viewing Plane X = 31.954 in.

Figure 4.6.15. Computation EF04. The XZ Shear Stress (psi).
Viewing Plane $X = 31.954$ in.

4.7 COMPUTATION TF04 (Reference 17)

Loading: Toroidal field

Geometry: Coil with dewar (located along $0 \leq \theta \leq 107.1^\circ$, the outer diameter of dewar is thereafter maintained at $z = \text{constant}$ to $y = 0$ while the inner diameter of dewar remains parallel to the inner diameter of the coil), shear panels (located along $0 \leq \theta \leq 98.6^\circ$), and bucking cylinder (parallel to the vertical leg)

Properties: $E_{\text{COIL}} = 25.29 \times 10^6 \text{ psi}$, $E_{\text{DEWAR}} = E_{\text{PANELS}} = E_{\text{SPOKES}} = E_{\text{CYLINDER}} = 30 \times 10^6 \text{ psi}$, $\nu = 0.3$ (everywhere)

Conditions: Load transferred from coil to dewar by axial load carrying spokes. The vertical leg of the coil is restrained by the bucking cylinder.

VERTICAL DIAMETER CHANGE = 0.135385 IN.
 HORIZONTAL DIAMETER CHANGE = 0.426848 IN.

Figure 4.7.1. Computation TF04. Displacements in the YZ Plane.
 Viewing Plane $X = 0$.

Figure 4.7.2. Computation TF04. The Y-Direction Normal Stress (psi). Viewing Plane $X = 6.4986$ in.

Figure 4.7.3. Computation TF04. The Z-Direction Normal Stress (psi). Viewing Plane X = 6.4986 in.

Figure 4.7.4. Computation TF04. The XY Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

Figure 4.7.5. Computation TF04. The YZ Shear Stress (psi).
Viewing Plane X = 6.4986 in.

Figure 4.7.6. Computation TF04. The XZ Shear Stress (psi).
Viewing Plane $X = 6.4986$ in.

5.0 REFERENCES

- 1) R. W. Moses, Jr., and W. C. Young, "Analytical Expressions for Magnetic Forces on Sectorized Toroidal Coils," Proceeding of the Sixth Symposium on Engineering Problems of Fusion Research, IEEE Nuclear and Plasma Sciences Society (November 1975).
- 2) J. A. Swanson and G. J. DeSalvo, "ANSYS, Engineering Analysis Systems User's Manual," Swanson Analysis Inc., Elizabeth, Pennsylvania 15037 (October 1972).
- 3) R. A. Smith, "Finite Element and Node Point Generation Computer Programs Used for the Design of Toroidal Field Coils in Tokamak Fusion Devices," WFPS-TME-001, Westinghouse Electric Corporation, P.O. Box 10864, Pittsburgh, Pa. 15236 (June 30, 1975).
- 4) R. A. Smith, "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, Westinghouse Electric Corporation, Fusion Power Systems Division, P. O. Box 10864, Pittsburgh, Pa. 15236 (June 30, 1975).
- 5) Computer Program PDXNODE, Run Number AN1RAAT, Geometry Generation Run for a D-Shaped Coil, (July 14, 1976).
- 6) Computer Program PDXFORC, Run Number ANRA16A, Toroidal Field Forces in the D-Shaped Coil Due to a Current of 8.54 Mega-amp turns through Each of Sixteen Coils, (July 30, 1976).
- 7) Computer Program PDXFORC, Run Number ANRA223, Lateral Forces in the D-shaped Coil due to a Vertical Field of 5,000 Gauss and a Current of 8.54 Mega-amp turns through Each of Sixteen Coils, (July 30, 1976).
- 8) Computer Program PDXFORC, Run Number ANRA12R, Forces on a D-Shaped Coil Adjacent to a Short-Circuited Coil and a Current of 8.54 Mega-amp turns through Each of Fifteen Coils, (August 11, 1976).

- 9) Computer Program PDXNODE, Run Numbers AN1RAIH and AN1RAYE, Geometry Generation Runs for Computations TF02, EF02, and ET02, (July 22 and 23, 1976).
- 10) Computer Program PDXNODE, Run Numbers AN1RA0K and AN1RFRK, Geometry Generation Runs for Computations EF03, EF04, and TF04 (August 10 and 13, 1976).
- 11) Computation TF01, Computer Program ANSYS, Run Number ANR5FCP, TF Loading of D-Shaped Coil with Wedging of Vertical Leg, (August 2, 1976)
- 12) Computation EF02, Computer Program ANSYS, Run Number ANR4FDW, EF Loading of Coil, Dewar, and Shear Panels located along $45^\circ \leq \theta \leq 90^\circ$ and with Load Transferred from Coil to Dewar by Coupled Nodes, (July 30, 1976).
- 13) Computation TF02, Computer Program ANSYS, Run Number ANR5FI6, TF Loading of Coil, Dewar, and Shear Panels Located Along $45^\circ \leq \theta \leq 90^\circ$ and with Load Transferred from Coil to Dewar by Coupled Nodes, (July 31, 1976).
- 14) Computation ET02, Computer Program ANSYS, Run Number ANRA1YN, Combined EF and TF Loading of Coil, Dewar, and Shear Panels Located Along $45^\circ \leq \theta \leq 90^\circ$ and with Load Transferred from Coil to Dewar by Coupled Nodes, (August 3, 1976).
- 15) Computation EF03, Computer Program ANSYS, Run Number ANR6FF8, EF Loading of the Coil, Dewar, and Shear Panels Located Along $0 \leq \theta \leq 98.6^\circ$, Load Transferred from Coil to Dewar by Spokes, and with the Vertical Leg Unrestrained. (August 17, 1976).
- 16) Computation EF04, Computer Program ANSYS, Run Number ANR7FXT, EF Loading of the Coil, Dewar, and Shear Panels Located Along $0 \leq \theta \leq 98.6^\circ$, Load Transferred from Coil to Dewar by Spokes, and with the Vertical Leg Restrained by the Bucking Cylinder. (August 18, 1976).

- 17) Computation TF04, Computer Program ANSYS, Run Number ANR8F4A, TF Loading of the Coil, Dewar, and Shear Panels Located Along $0 \leq \theta \leq 98.6^\circ$, Load Transferred from Coil to Dewar by Spokes, and with the Vertical Leg Restrained by the Bucking Cylinder but Without Wedging (August 19, 1976).
- 18) R. A. Smith, "Structural Analysis of TFTR Toroidal Field Coil Conceptual Design" WFPS TME-013, Westinghouse Electric Corporation, Fusion Power Systems, P.O. Box 10864, Pittsburgh, Pa. (October 1975)
- 19) "Handbook of Materials for Superconducting Machinery" Report MCIC-HB-04, Advanced Research Projects Agency, National Bureau of Standards (Oct. 1975).
- 20) R. E. Peterson, "Stress Concentration Design Factors," John Wiley and Sons, Inc., (1953).
- 21) Roark, "Formulas for Stress and Strain," McGraw Hill Book Company (1954).
- 22) R. P. Felgar, "Plastic Analysis of the Instability of Pressure Vessels Subjected to Internal Pressure and Axial Load," Journal of Basic Engineering, Transactions of the ASME, (June 1962).
- 23) Material Properties Data Book, Light Metal Alloys, Vol. 1, Report 2275, Aerojet Nuclear Systems Company (Nov. 15, 1970).

6.0 TABLES AND FIGURES

The section contains the tables and figures that are referenced in the text of Sections 1.0, 2.0 and 3.0.

TABLE 6-1

SUMMARY OF FORCES ON A COIL DUE TO THE
DIFFERENT LOADING CONDITIONS

LOADING CONDITION	VERTICAL EXTENSIVE FORCE (lbs)	CENTERING FORCE (lbs)	LATERAL FORCE (lbs)	OVERTURNING MOMENT (in-lbs)
Toroidal Field*	36.18×10^6	62.22×10^6	Zero	Zero
Fault**	31.23×10^6	52.12×10^6	49.28×10^6	Zero
Vertical Field***	Zero	Zero	8.29×10^6	3500×10^6

* See Figure 6-2

** See Figure 6-3 (Forces On a Coil Adjacent to a Short-Circuited Coil)

***See Figure 6-4

TABLE 6-2

SUMMARY OF THE PERTINENT DISPLACEMENT, STRESS, AND
LOAD RESULTS OF COMPUTATIONS TF01, TF02, AND TF04
(THE TOROIDAL FIELD LOADING OF THE TF COIL)

NO.		COMPUTATION		
		TF01	TF02	TF04
1	Vertical Diametral Expansion (in.)	0.163	0.242	0.136
2	Horizontal Diametral Expansion (in.)	0.439	0.264	0.427
3	Approx. Highest Z-Direction Stress (psi) in Vertical Leg of Coil (Assumed to be Homogenous, $E = 25.29 \times 10^6$ psi)	17000	17000	15000
4	Approx. Highest Normal Stress (psi) in Dewar (Assumed to be Steel, $E = 30 \times 10^6$ psi)	—	17000	Almost Zero
5	Approx. Highest Normal Stress (psi) in Shear Panel (Assumed to be Steel, $E = 30 \times 10^6$ psi)	—	17000	Almost Zero
6	Approx. Highest Stress (psi) in Bucking Cylinder (Assumed to have $E = 30 \times 10^6$ psi)	—	—	57000
7	Axial Load (lbs) in Bolt Simulations which Transfer Coil Loads to the Dewar	—	-6000	1194
8	Shear Load (lbs) in Bolt Simulations which Transfer Coil Loads to the Dewar	—	895376	Zero

TABLE 6-3

SUMMARY OF THE PERTINENT DISPLACEMENT, STRESS, AND
LOAD RESULTS OF COMPUTATIONS EF02, EF03, AND EF04
(THE VERTICAL FIELD LOADING OF THE TF COIL)

NO.		COMPUTATION		
		EF02 *	EF03 *	EF04 **
1	Slope Near Horizontal Mid-Plane of Outer Leg (millirad.)	10.038	1.024	0.998
2	Slope Near Horizontal Mid-Plane of Inner Leg (millirad.)	2.804	1.024	0.374
3	Approx. Highest Normal Stress (psi) in Coil (Assumed to be Homogenous, $E = 25 \cdot 29 \times 10^6$ psi)	15000	2000	1800
4	Approx. Highest Normal Stress (psi) in Dewar (Assumed to be Steel, $E = 30 \times 10^6$ psi)	72000	12000	8300
5	Approx. Highest Shear Stress (psi) in Shear Panel (Assumed to be Steel, $E = 30 \times 10^6$ psi)	22000	8000	7000
6	Approx. Highest Stress (psi) in Bucking Cylinder (Assumed to Have $E = 30 \times 10^6$ psi)	—	200	5000
7	Axial Load (lbs) in Bolt Simulations Which Transfer Coil Loads to the Dewar	101422	167648	112000
8	Shear Load (lbs) in Bolt Simulations Which Transfer Coil Loads to the Dewar	94598	Zero	Zero

* Inner leg restrained by wedging

** Inner leg restrained by bucking cylinder

TABLE 6-4
SUMMARY OF THE APPROXIMATE DISPLACEMENT, STRESS, AND
LOAD RESULTS OF THE COMBINED VERTICAL AND TOROIDAL
FIELD LOADING OF THE TF COIL SYSTEMS

NO.		COMPUTATION		
		TF01 and EF03 *	TF02 ^{**} and EF02 (ET02)	TF04 [*] and EF04 [*]
1	Vertical Diametral Expansion (in.)	0.163	0.242	0.136
2	Horizontal Diametral Expansion (in.)	0.439	0.264	0.427
3	Slope Near Horizontal Mid-Plane of Outer Leg (milliradians)	1.024	10.038	0.998
4	Slope Near Horizontal Mid-Plane of Inner Leg (milliradians)	1.024	2.804	0.374
5	Axial Load (lbs) in Bolt Simulations Which Transfer Coil Loads to the Dewar	168842	-100600	113200
6	Shear Load (lbs) in Bolt Simulations Which Transfer Coil Loads to the Dewar	Zero	990000	Zero

*Flexible coupling

**Rigid coupling

Figure 6-1. The Geometry for the Constant Tension D-Shape Coil
(For Computation TF01)

Figure 6-2. Low Field Design, In-Plane Force Distribution (KIPS/in.), with a Toroidal Field from 8.54 M-Amp Turns Per TF Coil in an Array of 16 Coils

Figure 6-3. Low Field Design, Out-of-Plane Force Distribution (KIPS/in.), in a Coil with 3.54 M-Amp Turns in an Array of 16 Coils Where this Coil is Adjacent to a Shorted (Faulted) TF Coil

Figure 6-4. Low Field Design, Out-of-Plane Force Distribution (KIPS/in.), with a Constant Vertical Field of 5000 Gauss, and with 8.54 M-Amp Turns Per TF Coil

Figure 6-5. The Coil Geometry for Computations EF02, TF02, and ET02.

Figure 6-7. The Coil Geometry for Computations EF03, EF04, and TF04.

SECTION A-A

SECTION B-B

SECTION C-C

Figure 6-8. Different Coil Cross-Sections
(Relate to Figure 6-7).

Figure 6-9. Present and Suggested Design for Positioning the Pancakes.

Figure 6-10. Suggested Design for the Locations and Shapes of the Shear Panels if the Neutral Beam Window Location can be at an Angle to the Horizontal Mid-Plane.

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