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UC-20D

TOROIDAL FIELD COIL DESIGN CONCEPT
AND STRUCTURAL SUPPORT SYSTEM FOR CTHR

DOE CTHR

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1.0 REACTOR APPLICATION

CTHR GENERAL DESCRIPTION

The Westinghouse Fusion Power Systems Department, under contract to the Department of Energy, Office of Fusion Energy, has been examining the technical and economic feasibility of fusion-fission hybrid reactors based on the tokamak concept since 1977. An important element of this work was the development of a reference first-generation Commercial Tokamak Hybrid Reactor (CTHR) design. The purpose of this reference design is to permit the identification of the technical features of such a system in sufficient detail to support an assessment of the potential availability of solutions to major design problems and to provide a benchmark estimate of economic feasibility. The work reported herein was performed as part of this overall effort. A summary of the CTHR plant point design is presented in the CTHR Final Report⁽¹⁾.

The CTHR conceptual design⁽¹⁾ consists of a magnetically confined (tokamak) fusion reactor fitted with a fertile uranium blanket. The fusion driver concept was based on an ignited plasma. All concepts and parameters were selected on the basis that technical feasibility would be achieved by 1995 to assure a viable commercial operation in the early to mid-21st century. The reactor was designed to achieve good fissile fuel production, with electricity production being a second order priority. However, the resulting concepts that evolved were all excellent power producers which significantly improved the economic performance. The subsystems discussed in the following paragraphs provide a background of the application for the TF coil design described in this report.

The CTHR has a major radius of 6.0 m with a minor radius of 1.4 m. The elongated plasma has an average ion temperature of 20 keV based on a parabolic profile and the electron density-confinement time product is $11.6 \times 10^{19} \text{ sm}^{-3}$. The fusion power is 1200 MW and the average neutron wall loading is 2 MW/m^2 . The significant plasma parameters are listed in Table 1-1. The

TABLE 1-1
CTHR FUSION DRIVER PLASMA PARAMETERS

MAJOR RADIUS, m	6.0
MINOR RADIUS, m	1.4
ASPECT RATIO	4.2
ELONGATION	1.6
PLASMA VOLUME, m ³	390
TOROIDAL FIELD ON AXIS, T	5.2
TOROIDAL FIELD ON COND., T	12.0
PLASMA CURRENT, MA	7.4
NEUTRAL BEAM ENERGY, keV (Negative Ion)	300
NEUTRAL BEAM POWER, MW _t (Startup)	84
PLASMA SAFETY FACTOR, q	2.9
PLASMA ENERGY GAIN, Q	IGNITED
AVERAGE ION TEMPERATURE, keV	20
AVERAGE ELECTRON TEMPERATURE, keV	16
PLASMA PROFILE	PARABOLIC
ELECTRON DENSITY, 10 ²⁰ m ⁻³ (n _e)	0.89
PLASMA β, Percent	6.0
POLOIDAL β	3.0
WALL LOADING, MW/m ²	2.0
FUSION POWER, MW _t	1200
ENERGY CONFINEMENT TIME (τ _E), s	1.3
n _e τ _E , 10 ¹⁹ m ⁻³ s	11.6
PLASMA PULSE DURATION, s (FLAT TOP BURN)	1200
PLASMA DUTY CYCLE FACTOR	0.95

fusion driver was developed with the maximum toroidal field at the conductor restricted to 12 tesla. This was felt to be a reasonable parameter for a first generation plant of a mature fusion industry in the 21st century.

A trimetric view of the reactor is shown in Figure 1-1. The 14 TF coils are equally spaced with a bundle divertor plasma exhaust system located between one pair. The 6.0 m device permitted sufficient room for the bundle divertor without using a larger angle between TF coils as had been done on the Demonstration Tokamak Hybrid Reactor (DTHR).⁽²⁾ The ripple is 2.9 percent peak to peak at the plasma edge. The four neutral beam injectors (NBI) are located beneath the reactor to maximize access to the blanket for refueling. The vacuum pumps are located adjacent to the NBI positions.

Figure 1-2 shows the elevation view cross section of the CTHR concept. The major subsystems features and parameters are given in Table 1-2. The reactor layout considered two major servicing operations. The first was the TF coil removal and replacement. The second was the more routine removal of the blanket sector during a refueling operation. The component locations, positionability and access were designed to achieve these operations. The CTHR radial dimensions and component thicknesses are presented in Table 1-3.

REACTOR SERVICING

The servicing of TF coils would normally be done in their operating position. However, if removal for major repairs or maintenance becomes necessary, a single coil or pair, could be removed from the reactor. The PF coils beneath the TF coils are lowered, using hydraulic rams, into recesses in the floor. The outer PF coils and upper PF coils are lowered or raised to clear the TF coils. Hydraulic rams could be used to do this also. The shear panels have a large bolt midway between TF coil pairs and a flanged dewar to permit detachment from the adjacent TF coil. A rolling dolly assembly is positioned beneath the TF coil on plates covering the lowered PF coils. The weight of the TF coil is then taken by slightly raising the inner leg of the coil off the central support structure. The outer support post has built in rollers.

Figure 1-1. Trimetric View of the CTHR

Figure 1-2. Elevation View of the CTHR.

TABLE 1-2

CTHR MAJOR SYSTEM FEATURES AND PARAMETERS

PLASMA OPERATION

Plasma Pulse Period	1268 s
Effective Burn Duration	1200 s
Recycle Time	56 s
Plasma Volume	390 m ³
Plasma Duty Cycle Factor	0.95
Design Basis Plant Availability	0.7
Design Basis Number of Pulses/Year	24,871
Pulse Scenario:	
Pulse OH (Bipolar)	2 s
Neutral Beam Injection (Heating to Steady State)	5 s
Burn	1200 s
Shutdown	5 s

TOROIDAL FIELD COILS

Number of Coils	14
Conductor Type	Nb ₃ Sn
Coil Shape	Compact "O"
Peak Field at Conductor	12 T
Current per Turn	20 kA
Average Current Density	3.3 kA/cm ²
Cooling Mode	Forced Flow Supercritical Helium
Structural Material	Stainless Steel 310

POLOIDAL FIELD SYSTEM

Conductor Material	Nb ₃ Sn
Location	Outside TF
OH Flux Swing	73.4/35.2 v-s
Conductor Current	10.35/16.7 kA
Average Current Density	4.0/4.5 kA/cm ²
Cooling Mode	Forced Flow Supercritical Helium

ELECTRICAL SYSTEMS

Utility Systems Interface	Operation - Baseline Startup - Utility Fed
S/C TF Supplies	Line-Driven Rectifier Supplies
Neutral Beam Supplies	Line-Driven Rectifier Supplies
Poloidal Field Power Supplies	AC-MG Storage-Rectifier Conversion
Main Generators	Rotors - Superconducting Stators - Copper

HEAT DISSIPATION SYSTEMS

Power Conversion System	Steam Cycle
Primary Reactor Coolant	Helium
Shield Coolant	Borated Water
Cryogenic Refrigeration Systems	L He; L N ₂
Facility Air Conditioning	Fixed Base Load, Reactor Cell "Air" Conditioning

NEUTRAL BEAM INJECTION LINES

Beam Power, Energy	84 MW, 300 keV
Single Arm Specifications:	
Sources	4-35 A Negative Ion
Vacuum Enclosure	8.0 m long x 2.5 m wide x 3.4 m high
Charge State of Source Ions	Negative
Number of Arms	4
Vessel Aperture Per Line	0.5 m x 0.9 m

PLASMA EXHAUST SYSTEM AND IMPURITY CONTROL

Bundle Divertor	Single Toroidal Position at Torus Mid-plane. Super-Conducting Nb ₃ Sn Circular Coils, On-Line Regenerable Zr Al Gettering, Cryopanel.
Throughput to Divertor Burial Chamber	~ 4.8 x 10 ²² Particles/s

TRITIUM SYSTEMS

On-Site T ₂ Inventory	Three Days (Initial Standby)
Tritium Storage	Uranium Chip Beds
Fuel Recovery-Recycling Plant	Continuous
Tritium Cleanup Systems	Reactor Torus/Inner Bldg./Coolants
Fueling	Prefill: Gaseous T Refueling: T Pellets and D-Beams and Pellets; 0.15 g/s

VACUUM VESSEL

Vessel Material	316-SS
Construction	Tubular/Flanged Sectors
Vessel Cross Section	D-Shaped
Composite Wall Thickness	0.5 m
Toroidal/Poloidal Limiters	Tungsten Rails (Radiation Cooled) 4 Locations
Vessel Coolant	Pressurized Helium
Coolant Inlet Temperature	350°C
Maximum Wall Temperature	528°C
Vessel Volume	480 m ³

VACUUM PUMPING

Pumping System	Cryosorption Pumps or Panels
Base Pressure	1 x 10 ⁻⁸ torr
Number of Pumps	8
Pumping Speed	8000 l/s
Operating Pressure	1 x 10 ⁻⁵ torr

TABLE 1-3
CTHR RADIAL DIMENSIONS

<u>COMPONENT/LOCATION</u>	<u>THICKNESS, cm</u>	<u>RADIUS, m</u>
Device Centerline	0	0
Bore		1.05
OH Coils (Within Bucking Rings)	26	1.60
Bucking Ring	65	1.70
TF Coil (Nose)	100	2.70
Dewar/Insulation	10	2.80
Assembly Gap	10	2.90
Inner Shield	60	3.50
Assembly Gap	15	3.65
Inner Blanket	53	4.18
Assembly Gap	12	4.30
Vacuum Vessel Flange	10	4.40
Scrape Off Layer	20	4.60
Plasma Minor Radius, a	142.5	
Major Radius, R_0		6.025
Plasma Minor Radius, a	142.5	7.45
Scrape Off Layer	20	7.65
Vacuum Vessel	10	7.75
Blanket (UC Cylinders)	34	8.35
(Manifold)	9	
Assembly Gap	8.5	8.435
Reflector/Lithium Blanket/Outer Shield	151.5	9.95
Assembly Gap	20	10.15
Dewar/Insulation	10	10.25
TF Coil	100	11.25
Beam Stiffener (at Cross Section)	45	11.70
Dewar/Insulation	10	11.80
PF Coil/Dewar Overhang (Beyond TF Coil)	~ 70	12.50

The reactor compartment crane would be used to stabilize the coil as it is rolled out from the reactor for servicing in an adjacent building. Removal of components inside the TF coil (shielding, blanket, vacuum vessel) is required if a single coil is removed. If a coil pair is removed then only partial disassembly from adjacent components may be necessary. The Neutral Beam Injectors are flanged near the shield valve and at the vacuum vessel to permit disassembly from the vacuum vessel. The TF coils have independent dewar (insulation) systems so that cryogenic conditions are maintained during blanket refueling or minor servicing of the TF coil system. However, during TF coil replacement, the entire cryogenic system would probably be shut down.

From the preceding discussion of the reactor concept and servicing considerations, it should be apparent that the TF coil design has a major impact on the reactor design and operation. Therefore, considerable design and analysis effort was made on the TF coil and its support structures to provide a firm foundation for the CTHR concept. This report provides an overview of many of these design considerations and a description of the resulting TF coil concept and parameters which were developed. A summary of the reference TF coil parameters is given in Section 5.0. Since the PF coil system relates very closely to the overall concept, a summary of the PF coils is also included in Section 5.0.

2.0 CTHR TF COIL NOSE SECTION DESIGN DEVELOPMENT

A key issue in the design of superconducting toroidal field coils for tokamaks is the treatment of centering force restraint. Solutions range from wedging the nose sections of adjacent coils to the use of a bucking cylinder which acts on the nose of each coil. Intermediate cases involving load-sharing through a combination of bucking and wedging have also been developed. The concept selected in the present design has all of the centering force loads during normal operation taken up by inter-coil wedging, which was determined to be the most efficient design approach considering radial thickness requirements at the coil nose area. Bucking rings were included as backup restraint for a faulted coil condition as well as a means of tension force removal for the compact "D" type⁽³⁾ TF coils.

There are two significant loadings which act on the TF coil nose section for the full wedging concept. The first is axial tension due to the magnetically induced forces in the coil. The second is hoop compression generated by the coil centering forces, which are created by the magnetic field of the coil array.

A computer program (MAFCO)⁽⁴⁾ has been used to calculate the magnetic fields and resulting forces on the TF coils. The coil model used is shown in Figure 2-1. Coil centering forces are calculated directly by the program. The tension force in the coil nose section is calculated from the code results in the following section. The CTHR TF coil parameters and resulting stresses determined in this analysis are summarized in Table 2-1.

2.1 CALCULATION OF TENSION IN TF COIL LEGS

The moments from the Z direction forces are shown in Table 2-2, while the r direction forces are shown in Table 2-3. These forces are based on MAFCO analysis of the CTHR design.

Circles indicate the centroid of arc segments or straight segments.

Figure 2-1. TF Coil Model Analyzed in MAFCO

TABLE 2-1
CTHR TF COIL PARAMETERS

COIL RESTRAINT - Full Wedging (Bucking Cylinder Backup)
CONDUCTOR SIZE - 6.3 cm^2 Square Superconducting Cable Slot
NUMBER OF TURNS - 558 (2 Turns per Slot - 11 Slots Max per Plate)
STRUCTURAL AREA - 0.6527 m^2
CONDUCTOR AREA - 0.3515 m^2
PLATE THICKNESS - 3.7 cm
MINIMUM PLATE WEB - 1.19 cm
MAXIMUM FIELD - 12 Tesla
CURRENT - 20 kA
TENSILE FORCE - 128.0 MN
CENTERING FORCE - 72.64 MN/m (Maximum Location)
TENSILE STRESS - 196 MPa
HOOP STRESS - -355 MPa
STRESS INTENSITY - 551 MPa
PLATE MATERIAL - 310 Stainless Steel Annealed Sheet
ALLOWABLE STRESS INTENSITY - 695 MPa
COIL RADIAL BUILD - 1.0 m

TABLE 2-2
MOMENT FROM Z FORCES

<u>FORCE, MNm⁻¹</u>		<u>LEVER ARM, m</u>		<u>MOMENT, MNm⁻¹</u>
<u>ARC 1</u>				
1.2364	x	10.737	=	13.275
3.7018	x	10.638	=	39.475
6.1972	x	10.440	=	64.699
8.7044	x	10.147	=	88.324
11.2450	x	9.764	=	109.796
13.8360	x	9.298	=	128.647
16.5020	x	8.757	=	144.508
19.2710	x	8.150	=	157.059
22.2210	x	7.487	=	166.369
25.4140	x	6.780	=	172.307
28.9750	x	6.041	=	175.038
33.1660	x	5.283	=	175.216
<u>190.4788</u>				<u>1434.713</u>

$$F_{z1} = (190.4788 \text{ MNm}^{-1})(5.85 \text{ m})\left(\frac{\pi}{24}\right) = 145.862 \text{ MN} \quad M_{\theta 1} = (1434.7125 \text{ MN})(5.85 \text{ m})\left(\frac{\pi}{24}\right) \\ = 1098.650 \text{ MNm}$$

<u>ARC 2</u>				
36.6000	x	4.547	=	166.457
39.0420	x	3.867	=	150.975
38.6940	x	3.256	=	125.988
34.3060	x	2.758	=	94.616
24.3940	x	2.406	=	58.692
8.9457	x	2.223	=	19.886
<u>181.9817</u>				<u>616.614</u>

$$F_{z2} = (181.9817 \text{ MNm}^{-1})(2.70 \text{ m})\left(\frac{\pi}{12}\right) = 128.635 \text{ MN} \quad M_{\theta 2} = (616.61408 \text{ MN})(5.85 \text{ m})\left(\frac{\pi}{12}\right) \\ = 944.36 \text{ MNm}$$

TOTALS:

$$F_z = 274.5 \text{ MN} ; \quad M_{\theta z} = 2043 \text{ MNm}$$

TABLE 2-3
MOMENT FROM r FORCES

			<u>F(MN)</u>	<u>F_{CUM}(MN)</u>	<u>Z(m)</u>	<u>M_{or} MNm</u>	<u>M_{or CUM} MNm</u>
<u>ARC 1</u>							
18.8640	(0.766)	=	14.445	14.445	0.383	5.335	5.533
18.6550	(0.766)	=	14.285	28.731	1.141	16.300	21.533
18.2560	(0.766)	=	13.980	42.731	1.880	26.282	48.114
17.6510	(0.766)	=	13.516	56.227	2.587	34.967	83.081
16.8300	(0.766)	=	12.888	69.115	3.250	41.885	124.967
15.7770	(0.766)	=	12.081	81.196	3.857	47.598	171.565
14.4720	(0.766)	=	11.082	92.278	4.398	48.739	220.304
12.8770	(0.766)	=	9.861	102.139	4.864	47.963	268.266
10.9580	(0.766)	=	8.391	110.530	5.247	44.029	312.295
8.6268	(0.766)	=	6.606	117.136	5.540	36.598	349.893
5.7635	(0.766)	=	4.413	121.550	5.738	25.325	374.218
2.1738	(0.766)	=	1.665	123.214	5.837	9.716	383.934

ARC 2

- 4.8185	(0.707)	=	- 3.406	119.808	5.872	- 19.847	364.087
-16.1720	(0.707)	=	-11.431	108.377	5.644	- 64.518	299.569
-29.6910	(0.707)	=	-20.987	87.390	5.292	-111.065	188.504
-44.7080	(0.707)	=	-31.602	55.788	4.794	-151.501	37.003
-58.8930	(0.707)	=	-41.629	14.159	4.183	-174.134	-137.131
-20.0300*	(0.707)	=	-14.159*	0.000*	3.502*	-49.583*	-186.715*

Thus $M_{or} = -186.7 \text{ MNm}$

*The net negative force calculated by MAFCO is cancelled by the structural restraint at the center of the coil array. Thus, since the last segment of ARC 2 causes the cumulative force to become negative, only a portion of the force in this final segment is active. The final row of numbers were adjusted to reflect this. All of the forces along the straight inner leg are cancelled by structural restraint so they do not appear in this tabulation.

$$F_z = \sum F_{zi} = 274.5 \text{ MN}$$

$$M\theta = \sum (M\theta_{zi} + M\theta_{ri}) = 2043.0 \text{ MNm} - 186.7 \text{ MNm} = 1856.3 \text{ MNm}$$

$$F_r = 0.0$$

The vertical forces must be canceled by the tension forces on the inner leg (F_i) and the outer leg (F_o), such that $F_z = F_i + F_o$.

The moment must also cancel, thus, $M\theta = 2.20 F_i + 10.75 F_o$.

Solving for F_i and F_o gives: $F_o = 146.5 \text{ MN}$ and $F_i = 128.0 \text{ MN}$.

Figure 2-2 and 2-3 give two possible plate-conductor layouts. The first uses 3.5 cm plates and is shown with 556 turns of 6.3 cm² superconducting cable. This design has the potential for 604 turns. The second concept uses 3.7 cm plates and 558 turns of the 6.3 cm² superconducting cable. The advantage of the second design is a 20 percent thicker minimum plate web. This could be of significant value during coil construction and handling and therefore, this alternative was selected as the reference design.

2.2 CONVERSION OF CENTERING FORCES TO HOOP COMPRESSIVE FORCES

A force balance from the figure of the nose section below gives:

$$2 F_s \sin \theta = F_{\text{center}}; \text{ therefore, } F_s = \frac{F_{\text{center}}}{2 \sin \theta}$$

The compressive force acting on the center plates is given by:

$$F_c = F_s \cos \theta = \frac{F_{\text{center}}}{2 \tan \theta} \quad \theta = \frac{360^\circ}{2n}, n = \text{number of coils}$$

Figure 2-2. Plate-Conductor Layout - Two Sizes of Plates

Figure 2-3. Plate-Conductor Layout With Uniform Plate Thickness

Conversion of Centering Forces to Hoop Compressive Forces

2.3 ANALYSIS OF CTHR TF COIL NOSE SECTION BASED ON MAFCO RESULTS

The tensile stress is determined using the area, $A_T = 0.6527 \text{ m}^2$ and the force, $F_T = 128.0 \text{ MN}$.

Stress
$$\sigma = \frac{F_T}{A_T} = \frac{128.0 \text{ MN}}{0.6527 \text{ m}^2} = 1.96 \times 10^8 \frac{\text{N}}{\text{m}^2} = 196 \text{ MPa}$$

Compressive stress is determined as follows:

Centering Force $F_{\text{center}} = 72.64 \text{ MN/m}$

Compressive Force
$$F_c = \frac{F_{\text{center}}}{2 \tan \theta} = \frac{-72.64 \text{ MN/m}}{2 \tan 12.86^\circ}$$

$$F_c = -159 \text{ MN/m}$$

Area
$$A_c = 0.4478 \text{ m}^2/\text{m}$$

Stress
$$\sigma_c = \frac{F_c}{A_c} = \frac{-159 \text{ MN/m}}{0.4478 \text{ m}^2/\text{m}} = -355 \text{ MPa}$$

The stress intensity is given by the following summation,

$$P = \sigma_T - \sigma_c = 551 \text{ MPa (79900 psi)}$$

Annealed 310 SS has a yield strength of 112 ksi at 4.3 K. Limiting the stress intensity to $0.9 S_y$ gives,

$$S = 0.9 (112000 \text{ psi}) = 100800 \text{ psi} = 695 \text{ MPa}$$

Since $P < S$, the design is satisfactory.

2.4 CONSIDERATION OF FULL BUCKING VERSUS FULL WEDGING

The preceeding analysis has assumed that the coil was under full wedging. The number of through bolts in the full wedging concept are less than in the full bucking concept since shear between plates can be transmitted by friction with full wedging. Shear loads between plates must be taken by the bolts in the full bucking concept.

The compressive stress in the full wedging concept is generated by the equilibrium forces at the coil interfaces. Thus, stress redistribution is possible at sights of locally high stress intensity. The small number of bolts and potential for stress redistribution makes it possible to ignore the bolt holes in the wedging stress analysis.

This is not the case for the full bucking concept. The compressive forces are generated uniformly through the length and thickness of each plate, so stress redistribution can not occur. Therefore, not only must the bolt holes be considered in the stress analysis, there will be more bolts to consider. Typically, the number of bolts in each row for the size coil considered here is five.

The average length of the five bolts is,

$$l_{ave} = \frac{0.776 \text{ m} + 1.23 \text{ m}}{2} = 1.003 \text{ m}$$

The area lost to the bolt holes is,

$$A_o = 5 l_{ave} d = (5) (1.003) (0.03175) = 0.1592 \text{ m}^2$$

The tensile area is,

$$A_T = 0.6527 - 0.1592 = 0.4935 \text{ m}^2$$

The tensile stress is,

$$\sigma_T = \frac{F_T}{A_T} = \frac{128.0 \text{ MN}}{0.4935 \text{ m}^2} = 259.4 \text{ MPa}$$

The centering force is transmitted through the plates to the bucking cylinder. Since the last row of bolts nearest the bucking cylinder is in a region of low magnetic field, it can be assumed that essentially all of the centering force must be transmitted through the thin web of the plates at the location of the last row of conductors. The structural area at this location is calculated as follows.

$$A_c = (21 \text{ bobbins}) \left(\frac{1.19 \text{ cm}}{\text{bobbin}} \right) = 24.99 \text{ cm} = 0.2499 \text{ m}$$

$$A_c = 0.2499 \frac{\text{m}^2}{\text{m}}$$

The compressive stress is,

$$\sigma = \frac{-72.64 \text{ MN/m}}{0.2499 \text{ m}^2/\text{m}} = -290.7 \frac{\text{MN}}{\text{m}^2} = -290.7 \text{ MPa}$$

The stress intensity is,

$$D = \sigma_T - \sigma_c = 547.6 \text{ MPa}$$

This value is less than the allowable value of 695 MPa for 310 SS material.

It should also be noted that the full bucking concept requires another structural member, the bucking cylinder, to restrain the coils. The structural bucking cylinder costs additional money, adds mass which must be cooled down and heated up, and restricts access to the OH coils in the bore.

The full wedging concept clearly represents a more efficient design which should result in a more cost effective machine.

2.5 COEFFICIENT OF FRICTION REQUIRED FOR FULL WEDGING

The reference CTHR TF windings design uses parallel sided plate bobbins. Only friction between the plates prevents relative motion for the full wedging concept. An estimate of the required friction coefficient follows.

Approximately 90 percent of all windings lie within the rectangular section of the TF coil nose section. It is therefore assumed that 0.9 of the centering force must be transmitted in shear through the two plate interfaces shown in the figure below.

The normal force on the two interfaces is,

$$F_c = \frac{f_{cen}}{2 \tan \theta}$$

The friction force which can be generated just before slipping is,

$$F_f = 2\mu F_c = \frac{\mu F_{cen}}{\tan \theta}$$

Thus, to just balance the centering force from the center windings,

$$F_f = 0.9 F_{cen}$$

$$\frac{\mu}{\tan \theta} = 0.9 F_{cen}$$

$$\mu = 0.9 \tan \theta$$

<u>N (coils)</u>	<u>θ(Degrees)</u>	<u>μ</u>
8	22.50	0.373
9	20.00	0.328
10	18.00	0.292
11	16.36	0.264
12	15.00	0.241
13	13.85	0.222
14	12.86	0.205
15	12.00	0.191
16	11.25	0.179

For a 14 coil design, a coefficient of friction of 0.205 or more will prevent sliding at the interface. This can be attained by judicious selection of materials, surface finish, and insulating coatings.

2.6 BOBBIN PLATE TOOTH LOADING FOR FULL WEDGING

The compressive hoop stress on each tooth is 355 MPa^(a). Each tooth is 2.98 cm long.

The maximum force acting on any tooth is due to the two conductors at the 12 tesla field portion of the coil.

$$P = 2 (12 \text{ T}) (20 \times 10^3 \text{ amps}) = 4.80 \times 10^5 \text{ N/m}$$

The frictional resisting force is,

$$F_f = 2\mu\sigma_c\ell$$

It has already been established that the full wedging concept needs a friction coefficient of at least 0.205 with 14 coils.

$$F_f = 2(0.205) (355 \times 10^6 \text{ N/m}^2) (0.0298 \text{ m}) = 4.34 \times 10^6 \text{ N/m}$$

Thus, the available friction force is an order of magnitude larger than the applied load. It can be assumed that the web does not take any load in tension.

(a) See Section 2.3.

A force applied at the center of the tooth will induce a moment which reduces the stress distribution at one point on the tooth face and raises it at another location.

The induced moment is,

$$M_I = p\delta = (4.80 \times 10^5 \text{ N/m})(0.00595 \text{ m}) = 2856 \frac{\text{Nm}}{\text{m}}$$

The unbalanced compressive stresses on the tooth are shown in the following sketch.

The resisting moment is given by,

$$M_R = 2\sigma l \left(\frac{2l}{3} - \frac{l}{2} \right) = 2\sigma l \left(\frac{4l}{6} - \frac{3l}{6} \right) = \frac{\sigma l^2}{3}$$

Equating moments,

$$\frac{\sigma l^2}{3} = p\delta$$

Solving for σ ,

$$\begin{aligned} \sigma &= \frac{3p\delta}{l^2} = \frac{(3)(4.80 \times 10^5 \text{ N/m})(0.595 \text{ cm})}{(2.98 \text{ cm})^2} \left(\frac{100 \text{ cm}}{\text{m}} \right) \\ &= 9.65 \times 10^6 \text{ N/m}^2 = 9.65 \text{ MPa} \end{aligned}$$

Compared to the normal compressive stress of 355 MPa, this is a small perturbation. It can be concluded from this analysis that the large compressive loads generated by full wedging are effective in restraining any moments due to eccentric loading of the plate teeth.

It has been assumed that the plate web does not contribute to the load restraint in the previous calculations. The web will be stressed in proportion to the fraction of additional stiffness it contributes to restraining the loads. Since the web is only 1.19 cm wide and the tooth face is 2.98 cm long, it is clear that the web will not contribute much additional stiffness. Thus, the stresses in the plate web will be very small and can be neglected in this preliminary design and analysis.

2.7 COEFFICIENT OF FRICTION REQUIRED TO PREVENT FAULTED COIL EJECTION

It is assumed that for some unspecified reason one of the TF coils faults in such a manner that its magnetic field ceases to exist. The centering force, which normally maintains the coil in equilibrium with the other coils of the array, drops to zero. The force balance at the coil interfaces must now be maintained by friction on the interface surface. Since the adjoining coils to

the faulted coil will still exert approximately the same force on the interface, the forces acting on the coil are as shown below.

Equating forces in the x and y direction to zero,

$$\Sigma F_x = 0$$

$$F_S \cos \theta + F_T \sin \theta - F_S \cos \theta - F_T \sin \theta = 0$$

$$0 = 0$$

$$\Sigma F_y = 0$$

$$2F_S \sin \theta - 2F_T \cos \theta = 0$$

$$F_T = F_S \tan \theta$$

But the force F_T is a frictional force generated by the normal force F_S .

$$F_T = \mu F_S$$

Thus,

$$\mu F_S = F_S \tan \theta$$

$$\mu = \tan \theta$$

<u>N (coils)</u>	<u>θ(Degrees)</u>	<u>μ</u>
8	22.50	0.414
9	20.00	0.364
10	18.00	0.325
11	16.36	0.294
12	15.00	0.268
13	13.85	0.246
14	12.86	0.228
15	12.00	0.213
16	11.25	0.199

For a 14 coil array, a friction coefficient of 0.228 or more will prevent sliding on the interface and consequent ejection of the faulted coil. If this friction coefficient is not sufficient, it will be necessary to provide a central "bucking" cylinder to prevent the consequent disarray of the remaining coils if the faulted coil wedging support is lost. Although typical values for the coefficient of friction for steel on steel are in the 0.7-0.8 range for a dry and static condition, it must be assumed that non-ideal conditions may occur with condensation present and faulted condition forces sufficient to cause infinitesimal movement. This can reduce the coefficient to the 0.2 range. Therefore, a bucking ring concept was developed to assure control during a faulted coil condition.

2.8 BUCKING RING AND CENTER OH COIL SYSTEM INTERFACE FEASIBILITY

The center column is comprised of 51 rings. Each ring is 25 cm high and contains a groove for three OH coil bobbins with each bobbin containing 12 conductor turns. The center column rings are divided into halves to provide discontinuity of the ring. Figures 2-4 and 2-5 show details of a typical bucking ring and the stacking arrangement of the rings. Figure 2-5 also shows the conductor and helium coolant system for a particular ring. The conductor lead-in and lead-out exit from the stacked array by means of slots cut into the external face of the rings. The helium coolant lines traverse the inner

Figure 2-4. CTHR Bucking Ring

All Dimensions in Centimeters

Figure 2-5. CTHR Bucking Ring/OH Coils

bore of the bucking rings. Figure 2-6 is a schematic of the electrical leads leading to and from the stacked array of bucking rings. The dots on the schematic represent the junctions which connect the leads of each bobbin together and provide coolant connections to the electrical conductors. Figure 2-5 shows a typical bobbin construction.

The dimensions noted on the sketches were calculated on the following design assumptions:

- Bucking Force per TF Coil - 70 MN per meter of vertical height.
- Material - 316 Stainless Steel - $S_u = 413 \text{ MPa (60,000 psi)}$
 - $S_y = 206 \text{ MPa (30,000 psi)}$

The bucking ring concept allows the OH coils to remain adjacent to the TF coils, provides a good structural housing for the coils and provides the desired faulted TF coil retention capability. The bucking rings and OH coils are mounted on and supported by the center column support, which also supports the inner legs of the TF coils. The support structures are discussed in the following sections.

Figure 2-6. OH Coil Wiring Schematic

3.0 CTHR TF COIL STRUCTURAL SUPPORT COMPONENT DESIGN DEVELOPMENT

The structural components described in this report were developed as part of the CTHR design study. In some cases several concepts of each component are discussed and evaluated. The structural component concepts consist of vertical support posts for the TF coils; a vertical support for the center column or bucking cylinder; a structural support to resist the out of plane forces on the TF coils and support the plates (bobbins) of each TF coil; a shear panel to restrain the overturning of TF coils; and a center cylinder for resisting TF coil twisting.

3.1 VERTICAL SUPPORT POST CONCEPTS FOR THE TF COILS

Two concepts were developed for this component. The primary objectives considered in the design were; a) develop a support that would carry the weight of the individual TF coils and provide stability; b) minimize the heat transfer through the support; c) provide a means of allowing the TF coil to expand or contract without applying undue stresses to the TF coils or the TF coil support and d) design the components for ease of remote handling and servicing of the tokamak. Figures 3-1 and 3-2 show the detail of two vertical support concepts that meet these requirements. The location of the supports on the TF coils will be discussed later. The vertical support shown in Figure 3-1 consists of a rectangular post attached to the bottom of the TF coil. The end of the post is seated at the bottom of a "U" shaped structure which in turn is supported at its open end by two vertical plate structures attached to a base plate stiffened by gussets. The contact points between the post and the bottom of the "U", and between the open ends of the "U" and the vertical plates are curved surfaces. This arrangement forms a swing that permits the center post (attached to the TF coils) to move in a horizontal direction while the "U" shaped structure moves, in pendulum fashion, between the vertical side plates attached to the base which is fixed to the foundation. Surrounding the entire support is a bellows type dewar to provide the thermal isolation. The orientation of the base and vertical plates are such that the radial expansion

Figure 3-1. Alternate Support Post - TF Coil

All Dimensions in Meters

Figure 3-2. CTHR TF Coil Support Post

or contraction of the TF coils will cause the swing action to be parallel with the radial direction of the TF coil.

Figure 3-2, the second concept, consists of three cylinders fitted within each other. The inner most cylinder is flanged at one end and attaches to the bottom surface of the TF coil. The outer cylinder, also flanged, is attached to two roller units each capable of supporting 453 tonnes. The roller assemblies provide for the radial movement of the TF coils. The intermediate cylinder is flanged at both ends. One end has an external flange while the other end has an internal flange. The flanges on the intermediate cylinder couple together the inner and outer cylinders. Spacer rings of insulating materials, used at the top and bottom of the assembly to position the cylinders symmetrically, prevent the cylinders from shifting as the TF coil expands or contracts. In this concept a cylindrical dewar surrounds the entire assembly.

The dimensions of the TF coils vertical support components shown in Figure 3-1 and 3-2 are based on the following design assumptions:

Wt. per TF Coil (Base on 14 TF Coil Tokamak) = 516 Tonnes

Material - 316 Stainless Steel - $S_y = 413 \text{ MPa (60,000 psi)}$

- $S_s = 206 \text{ MPa (30,000 psi)}$

Factor of Safety = 2

Coefficient of Thermal Conductivity (k) for S.S. at $100^\circ = \frac{0.1W}{cm/K}$

The location and numbers of vertical supports were determined on a 14 coil tokamak with two TF coils supported by three supports as shown in Figure 3-3. A concept for vertically supporting the inner leg of the TF coil by the center column will be discussed in the center column support section.

$R_1 = 4.2 \text{ MN}$

$R_2 = 2.95 \text{ MN}$

TOTAL NUMBER OF
VERTICAL SUPPORTS
21

Figure 3-3. A TF Coil Vertical Support Concept

A preliminary calculation of the heat transfer (q), by conduction, through the 21 vertical supports is based on the following formula:

$$q = \frac{Ak (t_1 - t_2)}{X}$$

where

$$A = A \text{ equivalent} = \frac{l_1 A_1 + l_2 A_2 + l_3 A_3 + \dots}{l_1 + l_2 + l_3 + \dots}$$

$$t_1 = 300^\circ \text{ K and } t_2 = 4^\circ \text{ K}$$

X = overall length of flow path

The flow path assumed through the structure is shown in Figures 3-1 and 3-2. The heat transfer for each concept is as follows:

Figure 3-1 concept, $q = 1.89 \text{ kW per 21 supports}$

Figure 3-2 concept, $q = 2.25 \text{ kW per 21 supports}$

This heat will appear as a cooling load for the cryogenic system and must be minimized for economical system operation.

3.2 VERTICAL SUPPORT STRUCTURE FOR THE CENTER COLUMN

As with the TF coil vertical support posts, the center column support design objectives were to; a) develop a support system to carry the load of the center column plus the weight of the OH coils, and b) minimize the heat transfer through the support structure. In the case of the center column vertical support structure four concepts were considered. These designs are shown in Figures 3-4 through 3-7.

Figure 3-4 is a sketch of the first concept for the center column support structure and was designed to support the weight of the center column only. The design consisted of an inner cylinder fixed at one end to a base plate mounted to the foundation, an intermediate cylinder and a center column base

Figure 3-4. Center Support Column Concept 1

Figure 3-5. Center Support Column Concept 2

3-9

Figure 3-6. Center Support Column Concept 3

All Dimensions in Meters

Figure 3-7. CTHR Center Column Support

ring. The intermediate cylinder terminating with an internal and external flange transmitted the load from the center column base ring to the upper end of the inner cylinder and provided a long path for heat transfer. The dimensions noted on the sketch in Figure 3-4 were calculated with the following assumptions:

Wt. of the Center Column = 7.62 MN (777 tonnes)

Material - 316 Stainless Steel - $S_y = 413 \text{ MPa (60,000 psi)}$
 $S_s = 206 \text{ MPa (30,000 psi)}$

Factor of Safety = 2

Coefficient of Thermal Conductivity (k) for S.S. at $100^\circ \text{K} = \frac{0.1 \text{ W}}{\text{cm/K}}$

In addition to analyzing the system for compression, tension, shear and bending stresses the critical buckling load P' for the inner cylinder was determined as:

$$P' = \frac{\pi^2 EI}{4L^2} = 18,000 \text{ MN}$$

which well exceeds the design load of 58.8 MN.

The preliminary heat transfer calculation for the support is:

$$q = \frac{Ak(t_1 - t_2)}{X} = 0.64 \text{ kW}$$

It was noted that if the inner vertical support post for the TF coils could be eliminated the lower equilibrium coils could be located closer to the center column for better equilibrium of the plasma. The design was changed so that the weight of the inner legs of the TF coils would be carried by the center column support. This was accomplished by providing a circular ledge on the center column base ring to support the additional weight of the nose sections of the TF coils. This concept is shown in Figures 3-5, 3-6, and 3-7.

Recalculating the stresses using the additional load imposed by the TF coils showed that the bending moment at the flange sections for the intermediate cylinder (Figure 3-4) was excessive. This led to a modified center column support design shown in Figure 3-5. In this design 10 slots were added to the inner cylinder and to the base ring of the center column to accommodate internal and external gussets to re-enforce the flange sections of the intermediate cylinder. This concept was abandoned because of the massive size of the gussets.

A third concept developed is shown in Figure 3-6. This design resolved the problem of bending stress but introduced still another problem. The holes in the side of the cylinder attached to the base plate are so large that the material between holes in this area was inadequate to support the loads.

The problems associated with the designs shown in Figures 3-5 and 3-6 lead to the design of the center column support system shown in Figure 3-7. This design consists of a center column base ring equipped with ten bosses positioned at the bottom of the ring, which project radially inward from the inner circumference of the base ring. Gussets are mounted above the 27 cm diameter bosses to resist the shear forces. The base of the support structure consists of a cylinder mounted to a base fixed to the foundation. Ribs of I beam structure are welded to the outer surface of the cylinder to resist buckling of the cylinder and provide additional bearing surface at the top of the cylinder.

The vertical downward forces of the center column base ring are transmitted to the center cylinder by ten "U" bolts with saddle blocks as shown in Figure 3-7. A diameter of 11.3 cm (4.5") for the "U" bolts as well as the dimensions shown on the sketch have been calculated using the weight of the center column plus the reaction loads of 14 TF coils as:

$$7.62 \text{ MN} + 14 \times 2.1 \text{ MN} = 37 \text{ MN (3700 tonnes)}$$

The material, factor of safety and coefficient of thermal conductivity is the same as for previous designs. The heat transfer for this design, using the same formula as for the other designs, is:

$$q = 0.427 \text{ kW}$$

4.0 STRUCTURAL SUPPORT FOR TF COIL OUT-OF-PLANE FORCES

The structural support system for restraining the out-of-plane forces of the TF coil discussed in this section is the result of a combination of several possible schemes. The total support system consists of an integrated arrangement of strongback beams located on the top, bottom and outer edges of the TF coils with shear panels located between TF coils at the outer periphery of the TF coils and a scheme for counteracting the overturning forces on the TF coil inner legs. An overview of each concept and the analyses of key components will be discussed in the following sections. The TF coil restraint system is shown in Figure 4-1 with the centerbore components removed.

4.1 TF COIL BEAM STIFFENER

Figure 4-2 shows a cross-section of the beam stiffener. To develop a maximum moment of inertia for the vertical stiffener, the beam is trapezoidal in cross section with the longest side away from the tokamak centerline. The side angle selected for the increase in cross section is such that the distance between adjacent beams is the same as the distance between adjacent TF coils measured at the inner bore of the outer leg of the TF coils. This maintains the maximum access for blanket refueling operations. The forces acting on the TF coil are taken from the computer program MAFCO⁽⁴⁾ and are shown graphically located on the TF coils in Figure 4-3.

For each of the forces shown in Figure 4-3, a reaction force was calculated that was applied at the horizontal center line of the top (or bottom) beam stiffener and is shown in Figure 4-4. The forces acting on the outer leg of the TF coil are assumed to react on the top and bottom beam stiffener 8.2 m from the inner leg of the TF coils.

From the applied forces as noted on Figure 4-4 reactions R_1 and R_2 were calculated as 18.6 MN and 17.9 MN respectively. The maximum bending moment is

Figure 4-1. TF Coil Restraint System

Figure 4-2. TF Coil Side View

Figure 4-3. TF Coil Forces - MAFCO

Figure 4-4. TF Coil Forces - MAFCO

21.4 MNm and is located 2.4 m from the R_2 reaction. A cross section of the top and bottom beam is shown below and has a moment of inertia of $I = 0.0995 \text{ m}^4$.

The bending stresses on the beam due to the 21.4 MNm bending moment is:

$$S = \frac{21.4 \times 10^6 \times 0.617}{0.0995} = 133 \text{ MPa}$$

The 133 MPa stress is equivalent to a factor of safety of ~ 3.1 based on an allowable stress limit of 413 MPa.

The stresses on the beam located on the outer vertical leg of the TF coil are determined from the following analysis. The ends of the vertical beam are fixed against horizontal rotation by the shear panels.

The bending moment, M , created at the upper and lower ends of the stiffener are equal to $M = R_2 \times 6.4 \text{ m} = 17.9 \times 10^6 \times 6.4 = 114.6 \text{ MNm}$. The moment of inertia for a cross section of the beam is, $I = 0.3196 \text{ m}^4$.

Applying these values to the stress formula:

$$S = \frac{Mc}{I} = \frac{114.6 \times 10^6 \times 0.9472}{0.3196} = 340 \text{ MPa}$$

In addition to this bending stress a twisting stress is created by the reaction force acting on the curved section of the beam at a distance 1.5 m radially outboard from the connection point of the vertical beam and the top and bottom beam. See side view shown above.

$$T = 17.9 \times 10^6 \times 1.5 = 26.9 \text{ MNm}$$

The maximum stress on a trapezoidal section in torsion is:

$$S \sim \frac{(3a + 1.8b)}{8a^2 \times b^2}$$

$$\begin{aligned} a &= 0.85 \text{ m} \\ b &= 0.40 \text{ m} \end{aligned}$$

$$S = 26.9 \times 10^6 \left(\frac{3 \times 0.85 + 1.8 \times 0.4}{8 \times (0.85)^2 \times 0.4^2} \right) = 95 \text{ MPa}$$

Assuming the bending stress and torsional stress occur at the same place, the combined stress is:

$$\sigma = \frac{S_x + S_y}{2} + \left[\left(\frac{S_x - S_y}{2} \right)^2 + (S_s)^2 \right]^{\frac{1}{2}}$$

where

$$S_x = 340 \text{ MPa}$$

$$S_y = 0$$

$$S_s = 95 \text{ MPa}$$

Then

$$\sigma = \frac{340 \times 10^6}{2} + \left[\left(\frac{340 \times 10^6}{2} \right)^2 + (95 \times 10^6)^2 \right]^{\frac{1}{2}} = 365 \text{ MPa}$$

The allowable stress is 413 MPa.

4.2 SHEAR PANELS AND CENTER COLUMN RESTRAINT SYSTEM

The shear panel design concept is shown in Figure 4-1. The shear panels are approximately 1.5 m high x 0.32 m thick and are attached to the vertical beam stiffener by means of a dovetail arrangement to assure a rigid connection which will transmit the bending moment into the shear panel. The ends of the shear panels are stepped to accommodate the lug on the adjacent shear panel. The step at the end of the shear panels also permit misalignment and assembly tolerances between TF coils. The notched ends of the shear panels are connected by a bolt which joins the ends of one panel to the adjacent panel as shown in Figure 4-2. The shear panels are located above the vertical height of the inside bore of the TF coil to provide maximum access to the blanket

modules. Because the shear panels are a structural part of the TF coil beam stiffeners the shear panels are enclosed within an integral dewar system and are not removed for refueling operations. Removal of shear panels would only be required for removal of a TF coil and at that time only unbolting of a dewar panel flange and removal of the vertical bolts that connect one shear panel to an adjacent panel would be required.

Figures 1-2 and 4-5 show an elevation and plan view of a center column restraint system which prevents overturning of the inner legs of the TF coils. The top and bottom beams of four TF coils extend into the center of the support column. The extensions are offset to permit installation of a compression cylinder that is in contact with the four extensions. In operation, the overturning force of the TF coils is transmitted through the offset extension of the beam stiffener into the compression cylinder. This action, in turn, is opposed by the offset extension attached to the beam stiffener and TF coil located 180 degrees away. When the number of TF coils is not divisible by four (i.e. 14 coils as shown in Figure 4-5), the offset lugs can not be 180° opposing. Thus, this concept may be good for 16 or 12 coil devices, but poor for a 14 T.F. coil device.

The compression cylinders located at the top and bottom of the center column are not rotationally restrained by the center column; thus no twisting forces are transmitted to the center column. An alternate concept which transmits the twist to the center cylinder is discussed in the next section and was taken as the reference concept.

4.3 TORQUE CAPABILITY OF CENTER CYLINDER

A torsion tube concept was shown in Figure 1-2. Four straight torque lugs (Figure 5-3) extend from the upper and lower stiffener beams to transmit the TF coil twist to this cylinder. Applicable equations for the torsional loading of a circular shaft are:

$$\tau = \frac{Tr}{J}$$

$$T = \frac{r\theta}{l} = \frac{\tau}{G}$$

Figure 4-5. Top View - TF Coil Beam Extension (Lugs) Concept

For a solid circular shaft,

$$J = \frac{\pi r^4}{2}$$

$$\tau = \frac{2Tr}{\pi r^4} = \frac{2T}{\pi r^3}$$

Thus, for a given shear stress, the allowable torque is,

$$T = \frac{\pi r^3 \tau}{2}$$

Also,

$$\theta = \frac{l\tau}{rG}$$

$$G = \frac{E}{2(1 + \nu)}$$

Let $r = 1.05 \text{ m}$

$$E = 29 \times 10^6 \text{ psi} = 2 \times 10^5 \text{ MPa}$$

$$\nu = 0.3$$

$$\tau = 150,000 \text{ psi} = 1.03 \times 10^3 \text{ MPa}$$

$$l = 12.0 \text{ m}$$

Then

$$T = \frac{\pi(1.05 \text{ m})^3 (1.03 \times 10^9 \text{ N/m}^2)}{2} = 1.87 \times 10^9 \text{ MNm}$$

$$= 1870 \text{ MNm}$$

$$\theta = \frac{2l(1 + \nu)\tau}{rE} = \frac{(2)(12.0 \text{ m})(1.3)(1.03 \times 10^9 \text{ N/m}^2)}{(1.05 \text{ m})(2 \times 10^{11} \text{ N/m}^2)}$$

$$\theta = 0.153 \text{ rad} \sim 8.77^\circ$$

The twisting moment from each coil is 214.5 MNm as determined in Figures 4-6 and 4-7, and Tables 4-1 and 4-2. Thus, for a fourteen coil design,

$$T_{\text{Applied}} = (14) (214.5 \text{ MNm}) = 3003 \text{ MNm}$$

A central column will not support the applied torque by itself. Even if it were possible to support the torque, deflections at the outer edges of the coil could exceed reasonable limits. Thus, the central column will support a portion of the torque loads and the stiffener beams and shear panels must resist the remainder of the torque.

4.4 FINITE ELEMENT MODEL

The array of TF coils and shear panels represents an indeterminate elastic problem. Conservative approximations have been used to size the components. These approximations can insure adequate design for stresses but prediction of load path and deflection requires a more unified analysis. Finite element stress analysis provides the technique needed to perform this analysis.

The upper half of one TF coil along with its stiffener beam and shear panel was modeled using the WECAN Finite Element Code* as shown in Figure 4-8, 4-9 and 4-10. The model contains 434 elements and 746 node points. This is not a large number of elements considering the geometric complexity of the TF coil. The model is relatively coarse so stress results are not very accurate. The intent of this model is to gain some understanding of the load path through the coil array and the order of magnitude of the deflections.

Since the out of plane forces on the coil are anti-symmetric, anti-symmetric boundary conditions were imposed on the nodes along the horizontal centerline

*Westinghouse Proprietary Code

Figure 4-6. Distribution of Out-of-Plane Forces on CTHR TF Coil (Top Half)

VIEW LOOKING INTO COIL

$$\Sigma F_{\theta} = \underline{4.855 \text{ MN}} \rightarrow$$

FORCES IN MEGA NEWTONS

OVERTURNING MOMENT FROM TOP HALF = 4.70 MN-m

OVERTURNING MOMENT FOR ENTIRE COIL = 9.39 MN-m

Figure 4-7. Distribution of Out-of-Plane Forces on CTHR TF Coil (Top Half)

TABLE 4-1
OVERTURNING MOMENT ON CTHR TF COIL

<u>ARC 1</u>	<u>FORCE, MN/m</u>		<u>LEVER ARM, m</u>		<u>MOMENT, MNm/m</u>
	0.72131	x	0.3830	=	0.2763
	1.40320	x	1.1410	=	1.6011
	-0.86429	x	1.8800	=	- 1.6249
	-4.26640	x	2.5870	=	-11.0372
	-6.27340	x	3.2500	=	-20.3886
	-7.43010	x	3.8570	=	-28.6579
	-7.57320	x	4.3980	=	-33.3069
	-7.24800	x	4.8640	=	-35.2543
	-7.17370	x	5.2470	=	-37.6404
	-7.58220	x	5.5400	=	-42.0054
	-8.48720	x	5.7380	=	-48.6996
	-8.28840	x	5.8370	=	-48.3794

$$\text{TOTAL} = -305.117 \text{ MNm/m} \times 5.85 \text{ m} \times \frac{\pi}{24} = - 233.65 \text{ MNm}$$

ARC 2

1.7254	x	5.827	=	10.0539
13.7590	x	5.644	=	77.6558
18.3240	x	5.292	=	96.9706
15.3850	x	4.794	=	73.7557
9.9715	x	4.183	=	41.7108
5.2100	x	3.502	=	18.2454

$$\text{TOTAL} = 318.392 \text{ MNm/m} \times 2.70 \text{ m} \times \frac{\pi}{12} = 255.06 \text{ MNm}$$

STRAIGHT

2.9508	x	2.835	=	8.3655
2.4899	x	2.205	=	5.4902
2.6161	x	1.575	=	4.1204
2.9036	x	0.945	=	2.7439
1.1690	x	0.315	=	0.3682

$$\text{TOTAL} = 21.088 \text{ MNm/m} \times 0.63 \text{ m} = 13.29 \text{ MNm}$$

TOTAL MOMENT

$$M_r = 4.696 \text{ MNm (Top Half of Coil Only); } M_{\text{overturning}} = 9.392 \text{ MNm (for Full Coil)}$$

TABLE 4-2
TF COIL MOMENT ABOUT CENTER AXIS

<u>FORCE, MN/m</u>		<u>LEVER ARM, m</u>		<u>MOMENT, MNm/m</u>
<u>ARC 1</u>				
(0.72131)	x	10.737	=	7.7447
(1.40320)	x	10.638	=	14.9272
(-0.86429)	x	10.440	=	- 9.0232
(-4.26640)	x	10.147	=	-43.2910
(-6.27340)	x	9.764	=	-61.2530
(-7.43010)	x	9.298	=	-69.0850
(-7.57320)	x	8.757	=	-66.3190
(-7.24800)	x	8.150	=	-59.0710
(-7.17370)	x	7.487	=	-53.7090
(-7.58220)	x	6.780	=	-51.4070
(-8.48720)	x	6.041	=	-51.2710
(-8.28840)	x	5.283	=	-43.7880

$$\text{TOTAL} = -485.55 \text{ MNm/m} \times 5.85 \text{ m} \times \frac{\pi}{24} = -371.81 \text{ MNm}$$

<u>ARC 2</u>				
(1.7254)	x	4.548	=	7.8471
(13.7590)	x	3.867	=	53.2061
(18.3240)	x	3.256	=	59.6629
(15.3850)	x	2.758	=	42.4318
(9.9715)	x	2.406	=	23.9914
(5.2100)	x	2.223	=	11.5818

$$\text{TOTAL} = 198.72 \text{ MNm/m} \times 2.70 \text{ m} \times \frac{\pi}{12} = 140.48 \text{ MNm}$$

STRAIGHT

2.9508

2.4899

2.6161

2.9036

1.1690

12.1294

$$\text{TOTAL} = 12.1294 \text{ MNm/m} \times 2.20 \text{ m} \times 0.63 = 16.811 \text{ MNm}$$

TOTAL MOMENT

M = -214.5 MNm (Top Half of Coil Only)

Figure 4-8. Finite Element Model of the Top Half of a CTHR TF Coil

TF COIL AND SHEAR PANAL GEOMETRY PLOTS ***

GEOM PLOT 2 WECAN

Figure 4-9. TF Coil Finite Element Model From a Different Angle

Figure 4-10. CTHR TF Coil Shear Panel Model

in the vertical direction. Appropriate boundary conditions were applied along the coil nose region and at the ends of the shear panels to simulate the adjoining coils. The in-plane and out-of-plane loads applied to the coil model are identical to those given in other sections of this report.

The largest deflection occurs at the end of the shear panel. This point on the shear panel moves about 0.82 cm under the imposed loading. This is a small displacement considering that the coil is 13.6 m high.

Only the internal constraints of the coil array were modeled. There were no external support points in the model. This means that sufficient structural stiffness exists in the design to restrain all of the imposed loads without resorting to supports which attach to the containment building structure. Such supports would represent a significant heat leak to the cryogenic system.

5.0 CTHR TF/PF COIL CONCEPT SUMMARY

5.1 TF COILS

The major TF coil parameters are listed in Table 5-1. The nose cross section of the TF coil, which is a fully wedged concept, is shown in Figure 5-1. Cable placement considerations and the TF coil cross-section thickness were the controlling parameters in this selection. During loss of wedging due to a faulted TF coil, the forces resulting on the remaining coils led to the inclusion of bucking rings in the CTHR concept. Some of the rings are already required for the compact "D" shaped TF coils to support the transition from the outer leg radius to the vertical inner leg. The bucking rings were slotted to permit placement of the ohmic heating coils nearer the plasma. The cross-sectional design of the TF coil plates was dictated by the combined stress from the tension forces and the centering forces. The resulting Nb_3Sn superconducting TF cable design is specified in Table 5-2. The cable cross-section geometry is shown in Figure 5-2 for the TF and PF coil cables.

With the cross section of the TF coil established to provide structural support for the cables, the rigidity of the overall multiplied coil was evaluated for out-of-plane forces. Shear panels were added at the top and bottom of each coil to restrain the overturning moment caused by these out-of-plane forces. The shear panels were located above and below the access area for the blanket sectors. It was then determined that the bending at the mid-plane of the outer TF coil leg was excessive as was the bowing at the top and bottom of each TF coil. Since the plates could not resist these deflections, a stiffener beam was added which fits over the plate stack, resulting in a rigid cross section. Not only did the beams eliminate the bending and bowing, but they also provided a means of reacting the twisting motion between the top of the 14 TF coils and the bottom of the coils. A central torsion tube in the bore of the torus reacted part of this twisting. External supports from the TF coils to the reactor floor do not appear to be necessary since the coils will restrain the remainder of the twisting

Table 5-1
CTHR TOROIDAL FIELD COIL PARAMETERS

<u>PARAMETER</u>	<u>UNITS</u>	<u>VALUES</u>
Plasma Major Radius	m	6.0
Vertical Bore	m	10.19
Radial Bore	m	7.55
Central Field	T	5.2
Maximum Field	T	12
Number of Coils	--	14
Field Ripple (at Plasma Edge, Peak/Peak)	percent	2.9
Total Stored Energy	MJ	29,000
Stored Energy per Coil	MJ	2,100
Total Ampere Turns	MA-T	156
Ampere Turns per Coil	MA-T	11.1
Coil Cross-Section (Nose Region)	m	$1.23 \times 0.776 \times 1.0$
Mean Coil Circumference	m	31
Superconductor/Stabilizer	--	Nb ₃ Sn/Cu
Conductor/Shape	--	Cable/Square
Current Per Turn	kA	20
Conductor Area per Coil (Sheath I.D. Basis)	cm ²	2232
Charging Power Required	MW _e	33
Structure/Conductor Area Ratio (Nose Region)	--	1.86
Coil Construction	--	Slotted Plates
Structural Material	--	Stainless Steel (310)
Coil Tension (Max. per Coil on Inside Leg)	MN	128
Centering Force (Max. per Coil)	MN/m	73
Coil Weight (Tonnes per Coil)		
Conductor		55
Coil Structure		240
Stiffener Beam		215
Dewar		<u>33</u>
Total		543
Cooling	--	Forced Flow Supercritical Helium
He Refrigeration Power (All Coil Systems)	MW _e	28
N ₂ Refrigeration Power (All Coil Systems)	MW _e	2

Figure 5-1. CTHR TF Coil Nose Cross Section

TABLE 5-2

SPECIFICATIONS OF Nb₃Sn-Cu SUPERCONDUCTOR FOR THE CTHR TF COILS

Average Current Density ^(a) , A/cm ²	3333
S/C Operating Current Density, A/cm ²	62,500
Area of Conductor + He, cm ²	4.00
Superconductor Area ^(b) , cm ²	0.32
No. of Strands, Active (3 x 3 x 3 x 3 x 6)	486
Non-Active	81
Strand Diameter, cm	0.08
Conductor Hydraulic Diameter, cm	0.04
Conductor Void Fraction	0.3
No. of Slots per Bobbin	11 max.
No. of Conductors per Slot	2
Mean Circumference of Coil, m	31
Helium Flow Rate per Conductor, g/s	4.2
Helium Inlet Temperature, K	4.2
Helium Inlet Pressure, Atm	6

(a) Averaged over slot area (clearance, insulation, jacket, conductor, stabilizer and coolant) of 6 cm².

(b) Copper to noncopper area ratio is 0.83.

Figure 5-2. CTHR Nb₃Sn Cable Cross Sections

moments. Figure 5-3 shows the torque lug extensions from the stiffener beams (at the top and bottom) to the torsion tube. The torsion tube was shown in Figures 1-1 and 1-2.

Since the TF coils are cryogenic, it is necessary to minimize heat transfer to the reactor floor at the support positions for the coils. This was done by developing a heat resistant TF coil support post under each coil and a center column support within the cryo-cooled enclosure. The support posts were constructed of telescoping cylinders mounted on roller assemblies as shown in Figure 3-2 and used at the outer leg positions only. The center column support concept shown in Figure 3-7 minimized heat transfer by carrying the structural loads through slender U-bolts between lugs and saddle clamps. The center column support, OH coils, bucking rings and TF coil nose sections were all contained within a common dewar system at the bore of the torus, while the outer TF coil legs, stiffener beams, shear panels and support posts were insulated in individual, form fitting dewar systems. All the upper TF coil cables feed to the common central dewar where the transition cryogenic conduit runs from the reactor to the power supply building. The lower TF coil cables feed through dewar tubes near the posts to a common location under the reactor floor level for transition to the power supply systems.

The preliminary sizing of the TF coils was achieved using the COAST⁽⁵⁾ computer code. Detailed sizing and layout work then resulted in a fairly detailed TF coil concept. This concept was used as input data for a final magnetic force analysis to confirm the structural adequacy of the design. The magnetic forces on the PF coils and TF coil systems were computed by the MAFCO code⁽⁴⁾ in sufficient detail as required for the mechanical design of support and restraining components.

5.2 PF COILS

The PF coils are located in three general areas: the coils in the bore of the torus; the coils above and below the plasma; and the coils on the outer periphery of the TF coils. The PF coils located outside of the tokamak bore

Figure 5-3. Plain View of CTHR

have been grouped and assembled in common dewar systems. This provides several advantages:

- Reduces the space envelope required compared to individual dewars.
- Reduces the manufacturing cost by using common dewar walls, insulation, helium headers, etc.
- Easier handling for installation and removal.
- Better access for blanket refueling and TF coil removal by lifting or lowering a unitized assembly.

The majority of the OH coils (51 of 65) are located in the bore of the device in a vertical stack positioned in slots in the bucking rings as shown in Figure 2-5. The height of the stack "carries" the flux around the corner of the TF coils so that the next OH coil set can be located above and below the TF coils, outboard of the vertical leg. This enables a solid corner construction at the top and bottom of the TF coil vertical leg, which is required to transmit forces from the sharply curved portion of the D-shaped TF coils to the wedge region and bucking rings. The OH coils in the bore are considerably less expensive to manufacture than the larger diameter outboard coils. Locating the OH coils in slots in the bucking rings kept the coils approximately 40 cm closer to the plasma and resulted in several million dollars cost savings due to reduced power supply requirements. Each OH coil is constructed of bobbin assemblies stacked radially to achieve the required coil thickness. Cables and cryo-coolant lines are carried through slots in the bucking rings as shown in Figure 2-5. The upper coil cables are fed up to the common central cryogenic chamber. The lower coil cables feed down and across to the center of the central support structure to pass below the reactor to that common cryogenic chamber. The cryo-coolant lines are fed by manifold lines between the bucking rings and the torsion tube.

The superconducting Nb_3Sn PF coil and cable parameters are shown in Tables 5-3 and 5-4. Figure 5-2 shows the typical cable cross-section for PF and TF coil cables. The PF coil locations and respective currents are listed in Table 5-5. A cross-section view of the upper and lower PF coil assembly is shown in Figure 5-4. The peripheral PF coil assembly shown in Figure 5-5. One of the upper and lower OH coils is packaged in its own dewar. This coil is shown in Figure 5-6.

The PF coils are enclosed by form fitting dewars to permit removal of the coils for maintenance and refueling of the blanket. The magnetic forces acting on the coil assemblies are very large and will be reacted by the TF coil array. This means that the loads must pass from the 4K PF coil assembly structure through the dewar wall to room temperature then through the TF coil dewar to the 4K TF coil structure. The dewar walls are not capable of supporting such large loadings. Therefore, a support post has been designed to transmit loads through the dewar as shown in Figure 5-7. The area of contact is reduced at the 4K side to half the room temperature side area. This reduces the heat transfer area by taking advantage of the increased strength of the post material (310 SS) at 4K. An internal coolant passage is provided near the midpoint of the post for nitrogen cooling. This limits the heat transfer to the 4K structure. The support posts on the PF coils mate with identical support posts on the TF coils to transfer the magnetically induced forces between the cryogenic structures.

TABLE 5-3
CTHR SUPERCONDUCTING OH COIL PARAMETERS

Design Maximum Field, Tesla	4.9
Inner Radius, m	1.34
Outer Radius, m	1.60
Total Ampere-Turns, MA-T	61.3
Superconductor/Stabilizer	Nb ₃ Sn/Cu
Conductor/Shape	Cable/Square
Current per Turn, kA (Range)	10.35-14.33
Average Current Density: Conductor Stabilizer, and Coolant, A/cm ²	3970
Structural Material	Stainless Steel
Coils in Vertical Stack	51
Total Coils	65
Total Turns	4476
No. of Cooling Channels per Stack	10
Average Length of Cooling Channel, m	43 (Solenoid Coils)

TABLE 5-4

CTHR SUPERCONDUCTING SF COIL PARAMETERS

Design Maximum Field, Tesla	2
Total Ampere-Turns, MA-T	47.78
Superconductor/Stabilizer	Nb ₃ Sn/Cu
Current per Turn, kA (max)	16.17
Average Current Density: Conductor, Stabilizer, and Coolant, A/cm ²	4480
Structure Material	Stainless Steel
Total Coils	12
Total Turns	2776

SPECIFICATIONS OF THE SUPERCONDUCTOR CABLE
FOR THE OH AND SF COILS

	<u>OH</u>	<u>SF</u>
Average Current Density, A/cm ²	3970	4480
S/C Operating Current Density, kA/cm ²	533	720
Area of Conductor + He, cm ²	3.61	3.61
Superconductor Area, cm ²	0.0269	0.0269
Cu - to - non Cu Area Ratio	19.13	22.96
No. of Strands (3 x 3 x 3 x 3 x 7)	567	567
Strand Diameter, cm	0.069	0.069
Conductor Hydraulic Diameter, cm	0.083	0.083
Conductor Void Fraction	0.40	0.40
Helium Flow Rate per Conductor, g/s	2.5	2.5
Helium Inlet Temperature, K	4.2	4.2
Helium Inlet Pressure, atm	4	4

TABLE 5-5
CTHR PF COIL SYSTEMS: COIL LOCATIONS AND CURRENTS

OH Coil ^(a) No.	Radius R,m	Height Z,m	No. of Turns	Current MA-T
1	1.47	0.00	60	0.86
to	same	by 0.25 to	same	same
26	1.47	6.25	60	0.86
27	2.20	7.40	108	1.118
28	3.20	7.40	108	1.376
29	4.25	7.40	96	1.376
30	9.225	7.20	108	1.290
31	11.133	5.25	96	1.290
32	11.75	4.00	96	1.147
33	12.00	2.50	96	<u>1.147</u>

Total OH Current = 61.348

SF Coil ^(a) No.	Radius R,m	Height Z,m	No. of Turns	Current MA-T
1	2.70	7.50	360	+5.50 ^(b)
2	3.70	7.50	390	+6.25
3	5.00	7.50	360	+5.70
4	11.25	4.50	144	-2.25
5	11.75	3.00	120	-1.94
6	12.00	2.00	144	<u>-2.25</u>

Total SF Current = 47.78

(a) Upper and Lower SF/OH coil sets external to the bore are at the same radial locations but the negative vertical locations.

(b) Positive current has the same direction as plasma current.

Figure 5-4. Cross Section of the Upper PF Coil Assembly

Figure 5-5. Cross Section of Outer PF Coil Assembly

Figure 5-6. Peripheral OH Coil Cross Section

Figure 5-7. Support Post

6.0 CONCLUSIONS

The structural design concepts presented here attempt to resolve some of the mechanical design problems associated with the conceptual design of the CTHR. The design approach taken with the various structural components is basic and does not constitute a final design. The intent was merely to size the component and show that the concepts are feasible from a mechanical view point.

- The split plate design used by the Westinghouse LCP coil does not appear to give a reasonable radial build for the CTHR concept. Unsplit plates must be used at least in the coil nose section.
- Structural restraint of overturning and twisting moments on the coils is very difficult to design and analyze. It will probably require detailed finite element analysis to accurately characterize stresses, deflections, and optimum restraint location.
- The net overturning moment about the horizontal axis on the TF coils is not large.
- The tension along the circumference of the TF coils is not constant, which is consistent with compact D-shaped coils.
- The vertical forces on the SF coils are directed toward the midplane, while hoop stress causes the coils to expand.
- The full wedging concept appears to have a significant advantage over the full bucking concept since it has the potential for eliminating the bucking cylinder and simplifying construction. The wedging concept needs a moderate

coefficient of friction to be viable, but results of published experiments show this to be possible if a judicious selection of materials and coatings is made.

Areas requiring further study include the following items:

1. Alternate construction techniques such as a welded design should be investigated in lieu of the slotted bobbin concept.
2. Friction coefficients at liquid helium temperatures need investigation.
3. Forces generated by the "compact D" design need detailed investigation.
4. A complete stress analysis of a typical coil design should be made so that problem areas and support concepts can be better characterized.
5. A cryogenic to room temperature structural support concept should be developed to help in the structural restraint of the coils.
6. Further analysis of the concept covering thermal and cyclic stresses as well as considerations of the effects of cryogenic cooling and radiation should be made.
7. Triangular cut-outs were left at the top and bottom of the TF coil outer leg. This area was intended for the electrical connections and coolant lines to the TF coils. This is another area that should be investigated further.
8. The structural restraint of out-of-plane forces on large superconducting magnets is the single most difficult design problem. Significant effort should be expended in this area to identify and resolve the design problems.

9. Structural support for the top and bottom PF coils and the PF coils circumscribing the TF coils was not evaluated and further study is required.

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