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PURE TENSION SUPERCONDUCTING TOROIDAL-FIELD COIL SYSTEM DESIGN STUDIES FOR THE ARGONNE EXPERIMENTAL POWER REACTOR*

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Summary

As part of the Argonne Tokamak Experimental Power Reactor (TEPR) design studies, a toroidal field (TF) coil system has been designed. NbTi was chosen as the most suitable superconductor and 8T was regarded as a practical peak field level in this study. The 16-coil design was chosen as a reasonable compromise between 2% field ripple and 3 m access gap. To minimize the coil structure and the bending moments on the conductor, a pure tension coil shape is necessary. A correct approach for determining the pure tension coil profile in a bumpy TF coil system is given. Verification of the pure tension coil by a three-dimensional stress analysis is presented. For coil quench protection, a series-connected scheme is proposed.

Introduction

The toroidal-field coils must be superconducting if the Tokamak Experimental Power Reactor (TEPR) is to produce more power than it consumes. Since the reactor power density is proportional to B_t^4, the toroidal field level must be as high as possible. Coils of this size (~ 10 m) and stored energy (~ 15 GJ) must be designed with full stabilization to ensure coil protection and guarantee predictable magnet performance. It is found that, for a TEPR, fully stabilized coils can be designed and that, because of the large force and coil size, high current density is neither necessary nor desirable. The toroidal coils use NbTi as superconductor and copper as stabilizer. To evaluate full stabilization, the radiation-induced resistivity of stabilizer must be taken into consideration.

To reduce the coil peak stress and thus minimize the coil structure cross section, a pure tension coil shape with no bending moment is necessary. To determine the pure tension coil profile a new approach has been developed which includes the effect of coil bumpiness, the number of coils and coil cross section. A three-dimensional stress analysis verified that the coils indeed approach the pure tension criterion.

The toroidal field coils are subjected to rapidly pulsed superimposing field of the order 3 kG from the equilibrium coil, the ohmic-heating coil and the plasma current. Without a field shield, the coil heating due to these ac fields produces a large power dissipation and refrigeration requirement even though the associated temperature rise of the conductor is small. The hysteresis loss of the superconductor is also large unless small filaments are used and the conductor is graded. In addition, the superimposing field interacts with the toroidal coils producing a twisting torque on the toroidal coils. For these reasons, the ohmic-heating coil and the equilibrium coil must be

designed to produce minimum superimposing field on the toroidal coils.

A series-connected coil protection scheme is proposed. This scheme allows the stored energy to be rapidly dumped to a discharge resistor outside each TF coil to prevent excessive voltage under malfunction. The series connection also ensures that each coil carries equal current at all times so that no additional forces are generated in the event of a magnet quench.

Design Considerations

The dimensions of the TF-coil (TFC) system for the TEPR was the result of an iterative process involving the plasma physics and power performance, the blanket and shield design, requirements on the ohmic-heating coils, and access requirements. The power objectives of the TEPR can be satisfied by a circular cross-section plasma with a radius of $a = 2.1$ m. An additional 0.3 m is allowed to reduce the number of fast alpha particles striking the wall, so that the toroidal vacuum chamber has a radius $r_w = 2.4$ m. A blanket-plus-shield thickness of 1.0 m on the inside provides adequate protection for the superconducting coils, and a 1.3 m thickness on the outside allows added margin and accommodates breeding blankets. Access requirements for the neutral-beam injectors and for getting maintenance equipment between the TF coil and the blanket on the outside, together with the space requirements for the toroidal vacuum vessel and the blanket and shield, led to a choice of $R_{bore} = 7.7$ m for the minor bore of the TF coil. The radial location, R_{10} in Fig. 1a was determined by the requirements that the central coil radius be sufficiently large so that the ohmic-heating (OH) coils could provide the necessary magnetic flux to induce and drive the plasma current without requiring excessive fields in the OH coils and that the plasma volume be sufficiently large so that the power objectives of the TEPR are satisfied. An additional requirement upon the design was that approximately 3.0 m access, at the horizontal midplane, be available between adjacent TF coils. This access requirement can be satisfied with 16 TF coils with $R_{bore} = 7.7$ m, and with a maximum field ripple at the outer part of the plasma of approximately 2%. With these requirements, R_{bore}, R_{10}, and 16 coils, a pure-tension shape was determined by the procedure described in the next subsection. Table 1 lists the specifications and characteristics of the ANL-TEPR TF coils, and Figs. 1a and 1b illustrate the TFC design.

The ideal winding cross section is the trapezoidal-coil cross section, which for a given peak field, allows for the maximum toroidal field to be obtained. However, the trapezoidal coil winding presents some winding complications. For this study, a rectangular coil cross section has been selected. In the rectangular cross section, the conductor cross section must be distributed so as to minimize the flux leakage. This

Fig. 1a

NUMBER OF COILS = 16
PEAK FIELD = 75 KG
B_{ϕ_0} = 33.4 KG.

$J_{avg.}$ = 1280 AMP./cm²
EACH COIL CROSS SECTION = 0.5:0 m²
EACH COIL AMP.-TURNS = 6.54 x 10⁶ A.-T.
TOTAL AMP.-TURNS = 104.64 x 10⁶ A.-T.

R_{10} = 2.566 m RAD.
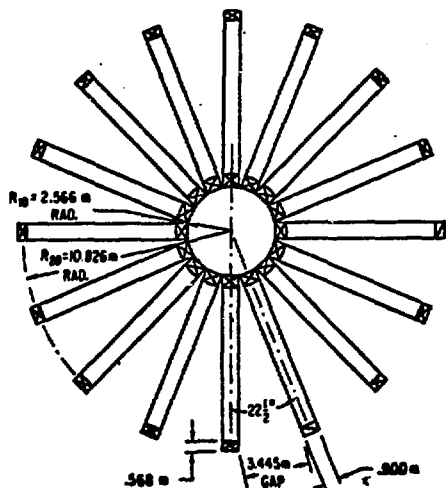R_{20} = 10.826 m RAD.

Fig. 1b
Schematic of TF Coils - Plan Cross Section

leads to a higher toroidal field in the plasma with given peak field. These points are illustrated in Fig. 2.

The Theory of Pure Tension Toroidal-Field Coils

The electromagnetic force acting on the circular toroidal coil is nonuniform with large bending moments

exerted on the coil, thus producing the peak stresses. For a given coil structure, significant decrease in the amount of structural material can be realized by reducing the peak stresses. The minimum peak stress is obtained when the stress is uniform; namely, the coil is in pure tension with no bending moments.

For a continuous toroidal magnet, the product $B_t r$ is constant within the coil winding. Therefore, the

Table 1   ANL-TEPR Toroidal Field-Coil System

Number of coils	16
Max. gap size	3.4 m
Field ripple	2%
Peak field	75 kG plus superimposed fields
Superconductor	NbTi plus copper stabilizer
R_{10}	2.566 m
R_{20}	10.846 m
R_{00}	5.47 m
B_t at plasma center	33.4 kG
Z_{max}	6.227 m
Radial thickness of coil plus bobbin	0.568 m
Axial length of coil plus bobbin	0.90 m
Ampere turns per coil	6.54 x 10⁶
Total ampere turns	104.64 x 10⁶
Cross section of coil plus bobbin	0.511 m²
Average current density over coil plus bobbin	1280 A/cm²
Winding cross section	0.44 m²
Average current density over coil winding	1486 A/cm²
Average current density over conductor	2378 A/cm²
Straight section length	7.28 m
Stored energy	15600 MJ
Operational current	10,000 A
Total inductance	312 H
Inductance per coil	19.5 H
Turns per coil	654
Mean turn length	34.4 m
Total conductor length per coil	22,500 m
Approximate weight per coil	175 tons
Total coil weight	2,800 tons

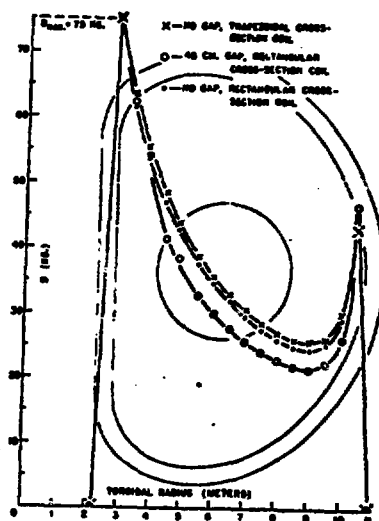

Fig. 2. Field Distribution in Plasma Column for Rectangular and Trapezoidal Coil Cross Section

transverse force, F_t, is given by

$$F_t = B_t I = \alpha r^{-1} \tag{1}$$

where r is the toroidal radius, B_t is toroidal field in the winding, α is a constant and I is the conductor current. When the coil is in pure tension, the natural conductor path must be that for which

$$\rho = \frac{Tension}{F_t} = kr = \pm \left[1 + \left(\frac{dz}{dr}\right)^2\right]^{3/2} \Bigg/ \frac{d^2z}{dr^2} \tag{2}$$

where ρ is the radius of curvature, k is a constant and z is the vertical coordinate. Coil shape, prescribed by equation (2), was first obtained by File et al.[1] Stress analysis[2] shows that the coil they obtained is not in pure tension for a torus with a finite number of coils. Considerable bending moments in the Princeton "Simple D" coil. Two assumptions they made are not strictly applicable to an actual toroidal field coil system. The field in the winding is not strictly inversely proportional to the toroidal radius, and the force per unit length of coil segment cannot be obtained by assuming the coil to be straight line segments. A second attempt was made by File et al.[3] to improve upon the first assumption. However, the equation presented in that paper diverges when one approaches the coil where the Lorentz forces are generated.

The shortcoming in the previous analysis[1,3] is in the evaluation of the field and force within the coil. For a bumpy toroidal coil configuration, the field variation across the winding is not inversely proportional to the toroidal radius. In fact, as shown in Fig. 3, the reciprocal field plot yields an almost straight line, but it does not pass through the origin. Furthermore, the slope of the line changes when the number of coils change.

To obtain the transverse force per unit length, F_t, it is necessary to integrate over the coil volume of a coil segment. It can be shown that

$$F_t(r) \cong (\delta_1 + \delta_2 r + \delta_3 r^2)^{-1}$$

so that equation (2) becomes

$$\rho = (\beta_1 + \beta_2 r + \beta_3 r^2) = \pm \left[1 + \left(\frac{dz}{dr}\right)^2\right]^{3/2} \Bigg/ \frac{d^2z}{dr^2} \tag{3}$$

The constant coefficients β_1, β_2, and β_3 are obtained through a least-square fit. Starting with the Princeton "Simple D" coil shape, a set of β's is obtained. Equation (3) is then solved. A new coil shape is obtained, and a new set of β coefficients is determined. Equation (3) is then solved. A new coil shape is obtained and a new set of β's is determined. Equation (3) is solved again, and so on. This iterative process continues until a set of β coefficients generates a nearly identical set of β's. Fig. 4 shows the evaluation of the Argonne pure-tension coil shape. This calculation is performed by the computer code, MARIA.[4] Fig. 5 shows various pure tension coil profiles vs number of coils. Note that the pure-tension

coil will approach the Princeton D if the coil number becomes large. On the other hand, it will approach circular coil shape if the coil number becomes 1. For the 16-coil pure-tension coil system, the computed field inside and outside the coil surface, the radius of curvature ρ, the transverse force F_t and the coil tension ρF_t are shown in Fig. 6. It is clear that the pure-tension coil behaves exactly like an ordinary solenoid.

Stress Analysis of Homogeneous Coils

The computer code MARIA, after generation of the Argonne pure-tension coil shape, divides the coil structure into many finite curvilinear elements. The computer code SOLID SAP[5] is then used to perform a three-dimensional stress analysis of the coil structure. A fairly uniform tension, with an average stress of about 16,000 psi, is obtained in the TF coil, as shown in Fig. 7. Based on same peak field, and coil cross section, stresses that would exist in a circular TF coil system and in a Princeton D coil system are also shown in Fig. 7. The coil support used in the stress evaluation is also shown in Fig. 7. Note the sharp reduction of peak stress in the Argonne pure-tension coil. If the coil profile has ~5 cm deviation above
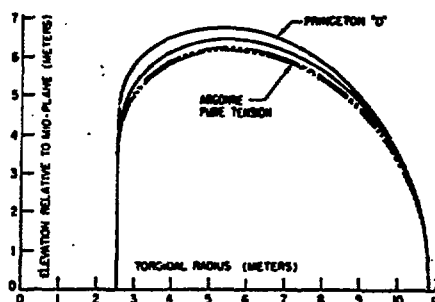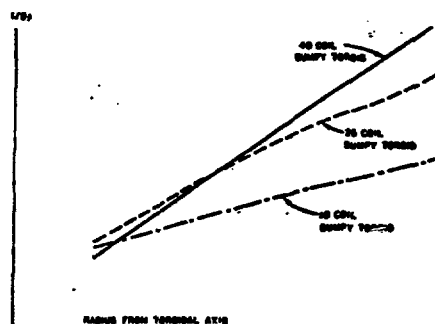

Fig. 3. Evolution of Pure Tension Coil

Fig. 4. Reciprocal Field Plots for Bumpy Toroids

the Argonne pure-tension coil, then the stress will have slight bending moments with stress ~2000 psi deviations from pure tension at a field level of 7.5 T. This is also shown in Fig. 7. The support system used in this stress analysis is indicated in Fig. 7. The θ is the termination angle of support. For circular coil, the support system extends to the top of the coil with support thickness of 1 m. For the Princeton D coil, the support extends to the tangent point with a support thickness equal to 1 m. For the Argonne pure-tension coil, the thickness of the support is only 30 cm. Note also that the position of the ends of the support cylinder is important in reducing the peak stress.

A reasonable stress limit for the copper is about 12,000 psi. To maintain this stress level in copper with an average stress of 16,000 psi, two parts of copper to one part of stainless steel are adequate, since the tensile modulus of stainless steel is about twice that of copper. The resulting stress of 24,000 psi on the stainless steel is well within its working limits at liquid helium temperature.
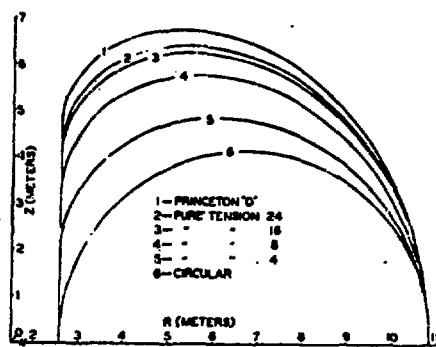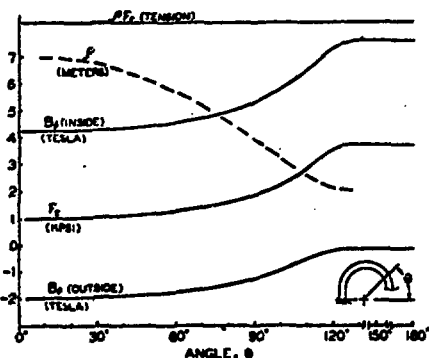
Coil Protection

With a total stored energy of 15,600 MJ in 16 coils, the energy per coil is 975 MJ. At a design current of 10,000 A, the inductance will be 19.5 H. By bringing a pair of leads out of each coil and allowing an energy-dump voltage of 1,000 volts per coil, the time constant of the TF system will be 195 sec or 3.25 min. The coils will be connected in series with a dump resistor between each coil as shown in Fig. 8. This method of connecting allows the energy to be removed rapidly enough to prevent damage to the coils under any malfunction condition and without accumulating a large voltage with respect to ground. It is important to keep equal currents in the coils at all times in order to prevent large induced-magnetic forces, which would damage the coils.

Interaction With Poloidal Field

The equilibrium coils, the plasma current and the ohmic-heating coils superimpose ac fields on the TF coil system as shown in Fig. 9. Note that the superimposing poloidal field has transverse and parallel field components. For ac loss estimation, we may
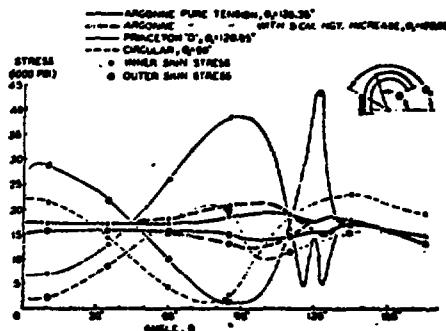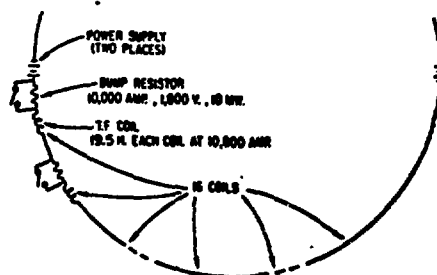
Fig. 5. Pure Tension Coil Shape vs Number of Coils

Fig. 7. Stress Analysis of Pure Tension Coil

Fig. 6. Pure Tension Coil Characteristics

Fig. 8. TF Coil Quench Protection System

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Fig. 9. Resultant Fields Due to OH Coils, Equilibrium Coils, and Plasma Poloidal Field

Fig. 10. General Cryostat Arrangement

assume that each TF coil is square. The two vertical legs are interacted by parallel fields of order of 3 kG. The upper and the lower arms of the TF coil are exposed to a time-varying field of 5 kG/sec. The amount of NbTi per coil is about $0.27 \, m^3$. The total composite volume per coil is about $10 \, m^3$.

The existence of 3 kG/sec parallel field will produce longitudinal coupling effects between filaments placed at different distances from the conductor axis. The coupling effect increases with conductor length. To reduce the coupling, the filament must be positioned at equal distance from conductor axis, or the twisting of filament must be reversed periodically.[6] These two approaches, however, may be impractical. To eliminate the longitudinal pulsing field, we propose the superconducting shield. A changing magnetic flux through a shorted coil will induce a current, which in turn will produce a flux opposing the applied flux. If the coil is superconducting, the current will be such as to exactly cancel the change in flux. A coil wrapped around the vertical legs of a TF coil will cancel the change in parallel fields automatically. Thus by winding around a TF coil with proper ampere-turns, one might expect to completely cancel the parallel fields.

To estimate the ac loss by transverse field, consider a field swing of $0 \to 5$ kG $\to 0$ and 10 µ filament size, the filament loss per coil is about 1400 J, or 22,400 J for 16 coils. To estimate the matrix loss, assume the twisting pitch is 2.5 cm, $\dot{B} = 5$ kG/sec and the matrix resistivity of 5×10^{-8} Ω-cm including the magneto-resistivity and induced resistivity by radiation, we obtain the matrix loss per coil ($10 \, m^3$ composite), over a complete fusion cycle, equal to 41,500 J, or 664,000 J for 16 coils.

In addition to the ac loss, the superimposed fields also exert bending and twisting torque on the TF coils.

Cryostat Design and Support System

The general cryostat arrangement is illustrated in Fig. 10. The individual TF coils will be supported by the support cylinder on the inside, and by individual supports on the outside. The support cylinder rests
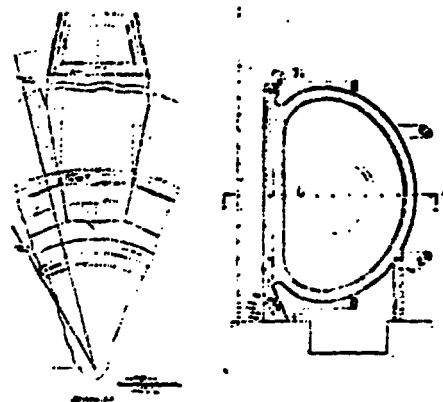
on a cylindrical compression member of low thermal-conductivity material. This support transmits the load to the outer wall of the vacuum jacket, which rests on the foundation.

The outer supports for the TF coils will be of the same material, again loaded primarily in compression and transmitting the load through the vacuum-jacket wall. The outer supports will be fixed to the TF coils through a hinged or sliding joint to allow for thermal contraction.

Each coil will have a separate helium container of stainless steel to minimize the helium volume. The container will conform closely to the coil geometry. The resulting flat-sided pressure vessel will require relatively thick walls.

The straight sections of the TF-coil conductor experience an inward centering force by Lorentz's law. Using an average field of 37.5 kG, a straight conductor length of 7.28 m, and a total ampere-turns of 104.6×10^5, the total centering force is 642×10^6 pounds. Since the inner radius of the support cylinder is 2 m and the outer radius is 2.28 m, the compressive pressure is 3970 psi and the maximum circumferential stress is about 34,000 psi. A metallic cylinder will be segmented to prevent induced currents from the ohmic-heating coils.

Each TF coil will be connected to its neighbors on either side by several cold supports on the outer portion of the coil. These supports plus some cross-bracing torque frame will be used to resist the twisting forces.

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