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TOROIDAL FIELD COIL SYSTEM OF THE OAK RIDGE EPR REFERENCE DESIGN*

J. W. Lue and J. N. Luton

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

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J. W. Lue and J. N. Luton†

ABSTRACT

A refined design of the toroidal field (TF) coil system for the Oak Ridge Tokamak Experimental Power reactor (EPR) study is presented. This design is based on cable conductor cooled by force-flow supercritical helium. It uses superconducting multifilamentary Nb_3Sn for a maximum design field of 11 T at the coil windings. A hybrid system which uses NbTi at low field regions is recommended. The coil structure consists of stainless steel segments welded together to form a continuous stiff honeycomb. Conductor optimization and stability analysis specifically applicable to the forced-flow cooled conductors are given.

I. INTRODUCTION

The scoping studies of the Oak Ridge EPR design team have resulted in the recommendation of a Reference Design,[1] which embodies advanced design concepts as well as traditional methods with the aim of obtaining a system that meets the various requirements. The goal has been achievement of a workable design rather than an optimized one. This paper describes the evaluation of the critical design features and the refining work on the TF coil system. Parametric studies, sensitivity checks, and detailed calculations were made,[2] and attention has been paid to the self-consistency and the extrapolatability of the system to larger demonstration and commercial power reactors. Special attention has also been given to the optimization and stability analysis of the forced-flow conductors used in the present design.

II. COIL SHAPE EVALUATION

After consideration of the factors of support structure cost, fabrication difficulties, and out-of-plane pulsed field loads, an oval shape was chosen for the TF coil in the original ORNL EPR Reference Design. A recent study by Moses and Young[3] has refined the 1/R toroidal field variation and derived an analytic expression for magnetic forces which takes into account the finite number of coils and the finite coil cross section. This expression is used to evaluate the oval coil shape. It is found that with a small curvature modification, the oval shape has a constant tension over 75% of its circumference. By fixing the maximum height and the outermost point, a constant tension is found to bend inwards short of the innermost point. A smooth curve is drawn between the bending and innermost points to complete the coil. This completed coil is shown in Fig. 1 together with a constant tension D-shape which has the same horizontal diameter. The D-shape produces 60% higher centering force and 28% higher stored magnetic energy than the oval shape. Furthermore, the taller D-shaped coil will be subjected to a larger flipping torque[2] by the out-of-plane pulsed field loads. It will also increase the ampere-turn requirements of the poloidal field coils, because a taller ohmic heating solenoid is needed. Therefore, the oval shape, which can be termed a modified D, is still judged to be a viable concept.

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†Superconducting Magnet Development Program, Thermonuclear Division, ORNL, Oak Ridge, TN 37830.

	"D"	"OVAL"
VARIATION OF TENSION	CONSTANT ALL THE WAY	CONSTANT FROM 3.4 m OUT
AVERAGE TENSION	91×10^6 N	76×10^6 N
CENTERING FORCE	350×10^6 N/coil	220×10^6 N/coil
CIRCUMFERENCE	34 m	30 m
TOTAL ENERGY STORED	37×10^9 joules	29×10^9 joules

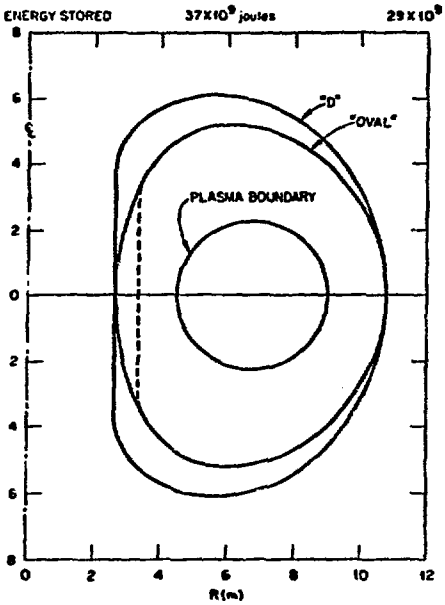

Fig. 1. Comparison of a constant tension D-shape to an oval shape for the TF coils. The dashed line shows the deviation of the oval shape from a constant tension D-shape. From this line out the oval shape has a constant tension.

III. COIL WINDING

The coil design is based on a bundled-cable conductor housed in a helium-tight jacket (aluminum alloy or stainless steel conduit), and cooled by forced-flow supercritical helium.[4] Because of the concern about possible strand motion inside the conduit, maximum cable size is set for a conductor current of 20 kA. Significant advantages can be obtained by winding several conductors in parallel. Aside from electrical (lower discharge voltage) and cooling (shorter cooling pathlength) advantages, multiple conductors wound in parallel reduce winding time and the amount of welding. Winding four conductor conduits in parallel and enclosing them in structural segments, as shown in Fig. 2, can result in considerable savings in time and cost. As the conductors are laid into position, stainless steel segments having an L-shaped cross section are pressed over the conductors and laser-welded into place. Additional welds are made across each segment, joining it to the previous segment. Grooves across the surface of the L-shaped structural segment are provided for auxiliary cooling and pre-cooling. Alternatively, the conductor conduit corners can be rounded if this poses no mechanical problems.

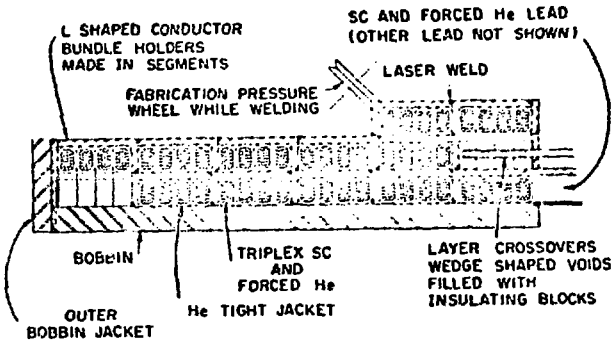

Fig. 2. Cross section of a partially wound TF coil.

It is desirable to grade the conductor in such a way that less expensive NbTi can be used in low-field regions, a technique which will also lower the ac losses (see Sect. VI). On the other hand, technology requires that splices should be kept to a minimum in a superconducting coil. These objectives can best be obtained by layer winding. A sizable saving in the pumping power can also be realized in the layer-wound scheme, as discussed in Sect. V. The mutual inductance difference in the layer arrangement of the conductors are small enough that the current imbalance between the conductor cables is negligible (<0.1%). Laser welding is chosen because the beam does not generate damaging heat to the insulation, it can be transmitted and focused from a distance, and it can be accurately aimed at a target. A fabricating pressure wheel holds the segments firmly in place while welding. Conductors must be sufficiently snug after welding to prevent movement when the coil is energized. The resulting honeycomb cross section is structurally robust and only a thin bobbin jacket is added to the completed coil as a secondary enclosure.

IV. CONDUCTOR DESIGN

It has been shown[4] that a cryostabilized conductor with current density up to 6000 A/cm² can be achieved in a bundled-cable conductor cooled by forced-flow supercritical helium. The large cooling surface areas of the small-diameter strands, plus a sufficiently high pressure drop to obtain moderate heat transfer coefficients, allow high stability limits. Recently, L. Dresner[5] found that it is possible to optimize these forced-flow cooled superconductors by varying the copper-to-superconductor ratio and/or the metal-to-helium ratio. For a given stability level, the pressure drop and pumping power may be substantially reduced by optimization.

Whether or not the superconductor can recover after a sudden temperature rise depends on a complicated competition between heat transfer from the metal to the helium and production of Joule heat in the metal. Each of these depends in turn on the cooled perimeter of the metal, the heat transfer coefficient, the helium inventory, the metal fraction, the normal conductor fraction of the metal, the normal conductor resistivity, and the current density. Furthermore, recovery occurs when the temperature falls to the current-sharing threshold, which depends on the current, the bath temperature, and the magnetic fields. With a given set of these parameters, it is possible to calculate the limiting heat input per unit volume of metal, ΔH_s, which can be deposited suddenly and uniformly over the entire length of the conductor and still allow it to recover the superconducting state. One way of optimizing the conductor is to vary the parameters to obtain a maximum ΔH_s with the minimum amount of required pumping power.

Figure 3 plots an example of the limit of sudden heat input, ΔH_s, from which the conductor can still recover to its superconducting state as a function of the normal metal (Cu) fraction, F_n, of the conductor. Starting with circular strands arranged in concentric layers in the conduit, the metal occupies about 76% (F_{co}) of the cable space. One can change this percentage by fluting grooves on the strands, as shown by the different F_{co} values. For each F_{co}, ΔH_s goes through a maximum as a function of F_n. This maximum first increases as F_{co} decreases and then decreases. Therefore, depending on the temperature, field, current density, and the operating heat transfer coefficient, h, there are optimum choices for both F_{co} and F_n. Also shown in the figure is a triplex strand configuration case, i.e., a strand which consists of three wires twisted together, which indicates a better margin of stability than the fluted strands. We have therefore chosen the triplex as the strand configuration. An additional advantage of this configuration is that one can make the triplex from two superconducting composite wires plus a normal metal (Cu or Al) wire to ease the manufacturing process. An aluminum wire would be a better choice for the stabilizer because of its higher conductivity at helium temperature and lower magnetoresistance. Since the technical compatibility of aluminum wire with superconducting wires has not been determined, our analysis was based on copper stabilizer.

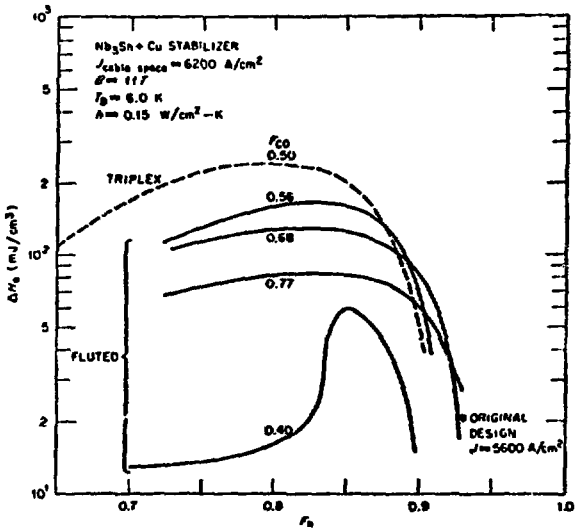

Fig. 3. Sudden heat input stability limit for fluted and triplex strand configurations. F_{co} = conductor (metal) fraction of the cable space, F_n = normal metal (copper) fraction of the conductor.

V. STABILITY AND PUMPING POWER

The stability of a forced-flow conductor depends not only on the configuration of the cable but also largely on how it is operated, particularly on the velocity of the helium flow and thus the amount of pumping power required. Figure 4 shows the functional dependence of ΔH_s on the pumping power, P_p, at a given

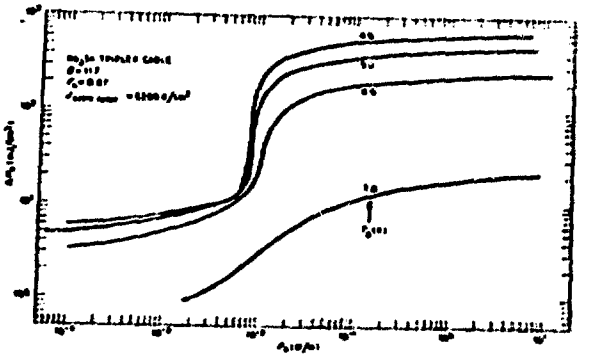

Fig. 4. Temperature variation of the sudden heat input limit dependence on the required pumping power.

field for different temperatures. Figure 5 shows the same dependence at a given temperature for different fields. A common feature of these curves is that although ΔH_g increases monotonically as P_p increases, it saturates fairly quickly. Large variation of ΔH_g occurs only in a range of P_p less than an order of magnitude, above that which corresponds to raise the conductor temperature to the superconducting critical temperature. One can thus limit the pumping power (and the helium flow velocity) to a value close to the top of this rapid variation range, without losing the stability capability of the conductor.

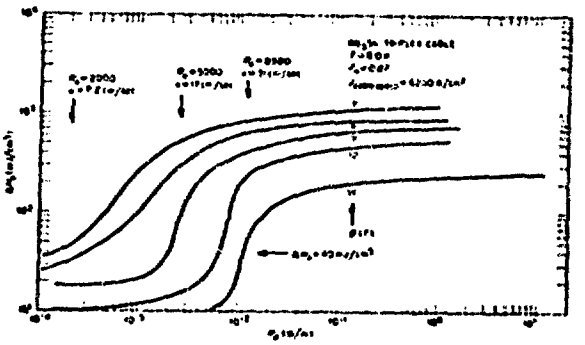

Fig. 5. Field variation of the sudden heat input limit dependence on the required pumping power. Locations of some Reynold's number, Re, and helium velocities, v, are indicated.

Figure 4 also shows that lowering the bath temperature will generally increase the stability limit. However, this trend slows down below a certain level. Once the bath temperature is low enough to achieve a critical current comfortably (20%) above the design current, it is not necessary to operate at even lower temperatures. Figure 5 shows similar trends as the magnetic field decreases. Inside the magnet winding, the field decreases from the inner layer to the outer layer. A reasonable operation is to assume a ΔH_g value near the top of steep variation for the highest field and maintain this ΔH_g throughout the coil. The layer wound arrangement enables us to pump the helium at lower velocities on successive layers with a substantial saving in pumping power. As shown in Fig. 5 for $\Delta H_g = 40$ mJ/cm^3, the pumping power required for $B \leq 9$ T is less than 2 mW/m. This corresponds to a Reynold's number slightly less than 5000. In order to assure a turbulent flow and thus the correct heat transfer coefficient used in the analysis, it would be wise to use a pumping power of at least 2.5 mW/m. Similar analysis has been performed on the NbTi superconductor at 6.5 T and below. An average pumping power of 6.3 mW/m and an average helium flow velocity of 24 cm/sec were obtained and were used for later calculations.

Calculations[4,5] also indicate that after a sudden heat input of the amount up to the limit discussed above, the conductor can recover to its superconducting state in tens of milliseconds. The sudden heat input stability limit discussed so far applies to unpredictable heat sources such as those due to flux jumps and conductor slippage. The slower heat inputs, such as those from ac losses and neutron heating, allow the helium to reach thermal equilibrium with the conductor are subject to another stability limit. This gradual heat input limit, ΔH_g, is the amount of heat that is required to raise the temperature of the helium (plus the conductor) to the current-sharing threshold of the superconductor. It is the asymptotic value of ΔH_g as P_p approaches infinity, shown in Fig. 4 and Fig. 5. This stability limit reflects the characteristics of the individual conductor and does not depend on the pumping power. However, because of the long helium path length (390 m in the present design), the total heat received by the helium in its transit through the conduit depends on the helium flow velocity. It is thus recommended that the magnet be operated with a pumping power that gives near-maximum ΔH_g at high fields and that arranges the cooling paths to stay comfortably below ΔH_g when subjected to the anticipated operation power input.

VI. AC LOSSES

The ac losses in the superconducting composite wire include hysteresis and coupling loss. They depend on the wire size, the superconductor filament size, the current densities, the twist pitch, and the field pulse. Because the pulse fields have components both perpendicular and parallel to the conductor, it is found that an optimum choice of filament twist pitch exists. Figure 6 shows the contribution of the two components as functions of the twist pitch parameter, γ_w. The loss due to perpendicular pulse field decreases with tighter twist,[6] while that due to parallel pulse field increases.[7] Thus, depending on the relative field pulse values, one can find optimum values for the twist pitch.

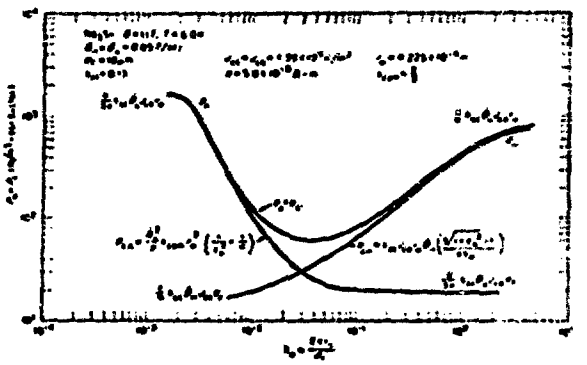

Fig. 6. Hysteresis and coupling losses in the superconducting wire. Both the functional dependence on the twist pitch parameter, γ_w, and the limiting equations are shown on this graph.

The total ac loss in the superconducting wire is calculated by multiplying a transport current increment factor, $[1 + (I_t/I_c)^2]$ to the sum of hysteresis and coupling loss. This product plus the eddy current losses in the copper wire and in the aluminum-alloy conduit gives the total ac loss in the conductor conduit. With a pulse field component of $\dot{B}_A = \dot{B}_{||} = 0.05$ T/sec for 2 seconds every 100 seconds, the average ac losses in the conduit are estimated to be 0.4 kW for the 20 coils. Because of the continuous coil structure, the eddy current loss is high. The eddy current loss in the stainless steel structure is averaged to about 0.9 kW, more than twice that in the conductor conduit.

VII. SUMMARY OF THE TF COILS

The analysis discussed above has led to a refinement of the TF coil design shown in Fig. 7. Each of the 20 TF coils has an oval shape with a vertical bore of 9.7 m and a horizontal bore of 7.4 m. The coil structure is a distributed stainless steel honeycomb constructed by welding L-shaped segments together. Four conductor conduits are layer-wound in parallel to form a 78 kA current path. There are 93 strands in a cable, arranged in six concentric circles, twisted in reverse directions on consecutive layers. Each strand consists of a triplex of two superconducting composite wires and one normal metal (Cu or Al) wire. For an average helium flow velocity of 24 cm/sec and pumping power of 6.3 mW/m, the sudden heat input limit at 4 K is about 300 mJ/cm³ of the cable conductor. Its gradual heat input limit is about 700 mJ/cm³. The total average ac losses of the TF coils are about 1.3 kW, while the total pumping power required is about 1.6 kW. Table I summarizes the physical parameters of the TF coils.

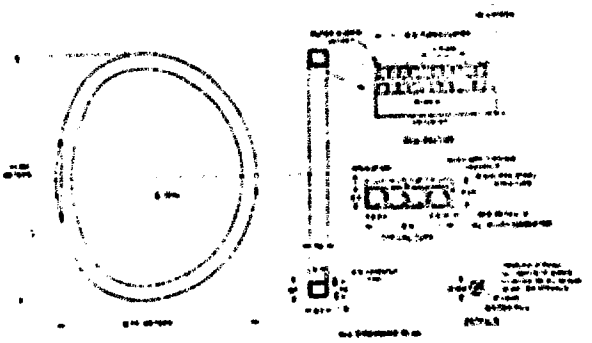

Fig. 7. Shape, winding, and conductor configuration of a TF coil.

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TABLE I
Physical Parameters of the TF Coils

Item	Value or Description
Overall	
Major radius (m), R_0	[illegible]
Maximum field at winding (T), B_m	[illegible]
Field at plasma axis (T), B_0	[illegible]
Number of coils	[illegible]
Coil shape	[illegible]
Core bores	[illegible]
Total average stored (MJ), B_0	[illegible]
Total ampere-turns	[illegible]
Conductor	
Winding dimensions (m)	[illegible]
Number of layers	[illegible]
Number of turns per layer	[illegible]
Superconductor	[illegible]
Conduit dimension (m)	[illegible]
Cable diameter (m)	[illegible]
Strand number	[illegible]
Strand diameter (m)	[illegible]
Strand configuration	[illegible]
Wire diameter (m)	[illegible]
Superconductor fraction of the conductor	[illegible]
Filament size	[illegible]
Current Densities	
Conductor cable current (kA), I	[illegible]
Overall current density (winding and coil case)	[illegible]
Current density over cable space	[illegible]
Cooling	
Cooled perimeter (m), P	[illegible]
Hydraulic diameter (m), D_{hy}	[illegible]
Coolant path	[illegible]
Average helium flow velocity (m/sec), v_{ave}	[illegible]
Average helium transit time (min)	[illegible]
Average pumping power required (MW), P_p	[illegible]
Average temperature rise to pumping loss (K)	[illegible]
Average temperature rise due to ac losses (mW/m)	[illegible]
Inlet helium temperature (K), T_{in}	[illegible]
Average steady-state heat transfer coefficient (W/cm²·K)	[illegible]

REFERENCES

1. M. Roberts and E. S. Bettis, Oak Ridge Tokamak Experimental Power Reactor Study Reference Design, ORNL/TM-5042, Oak Ridge (November 1975).

2. J. W. Luo (ed.), Oak Ridge Tokamak Experimental Power Reactor Study, Part 3 - Magnet Systems, ORNL/TM-5574, Oak Ridge (to be published).

3. R. W. Moses, Jr., and W. C. Young, "Analytic Expressions for Magnet Forces on Sectored Toroidal Coils," 6th Symposium on Engineering Problems of Fusion Research, p. 917 (1976).

4. M. O. Hoenig and D. B. Montgomery, "Dense Supercritical Helium Cooled Superconductors for Large High Field Stabilized Magnets," IEEE Trans. Magn. MAG-11, 569-575 (March 1975).

5. L. Dresner, "Stability-Optimized, Force-Cooled, Multifilamentary Superconductors," paper S1 of this conference.

6. G. H. Morgan, J. Appl. Phys. 41, 3673 (1970).

7. S. S. Shen and J. R. Miller, "Transient Poloidal Field Effects in Twisted Multifilamentary Superconductor for Toroidal Field Windgins of Tokamaks," Proc. 6th Symposium on Engineering Problems of Fusion Research, p. 145 (1976).