Modular Coil Design for UWTOR-M Stellarator Reactor

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MODULAR COIL DESIGN FOR UWTOR-M STELLARATOR REACTOR†

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Abstract

The latest developments in the conceptual modular coil design for UWTOR-M stellarator reactor are presented. The emphasis in the design is toward the modularity, maintainability and technology feasibility of the discrete windings. The stress and deformation of the coils are calculated and overall compatibility of the various components studied. The results show that all the preliminary design objectives can be met with reasonable cross sectional dimensions of the magnet structure. Although more refined studies are needed for the structural details, the study indicates that the envisaged design is feasible with moderate extrapolations to the present day technology.

Introduction

The design study of a steady state fusion power reactor UWTOR-M has been conducted by the University of Wisconsin Fusion Engineering Program in the past two years. This design employs the stellarator concept but adopts a modular coil configuration. Advantages of classical stellarator reactors, such as steady state operation with no disruption at ignition, no need of auxiliary and pulsed coils, reduced fatigue problem and simpler blanket design, etc., are maintained in this design. The modular configuration provides the further convenience of easy accessibility to blanket and shield. The latest design of UWTOR-M is divided into 18 integral modules consisting of coil, support structure, shield, blanket, divertor targets and coolant headers. Such modularity is very desirable for the ease of construction and maintenance of the reactor.

The success of the modular stellarator reactor concept, however, depends on a successful coil design to sustain the applied magnetic forces. Because of the twisted configuration of the modular coils, a unique magnetic force distribution acts on the coil which prevents any possible pure tension shapes of the magnets. This situation makes a credible design difficult. To achieve the structural design objectives of the modular coils in UWTOR-M, extra reinforcing structures will be needed. Such reinforcing structures should be effective in reducing the stress and deformation of the coil winding. At the same time, they must be compatible in space with other reactor components and still maintain the structural and cryogenic independence of each coil.

In this paper we present the latest design for the modular coil of UWTOR-M. The reinforcing structure and support concept are first described. The initial design for the coil case and its supporting structure is then given. The finite element analysis for the coil structure is described in some detail. The feasibility of the design is then verified through the results of the analysis. Some preliminary aspects of this design have been previously published [1].

Coil Configuration

The magnet configuration for UWTOR-M is shown in Fig. 1. This configuration approximates the classical stellarator continuous winding by 18 discrete coils. The geometry adopted follows the winding law presented in [2]. The magnet parameters for this design are given in Table 1.

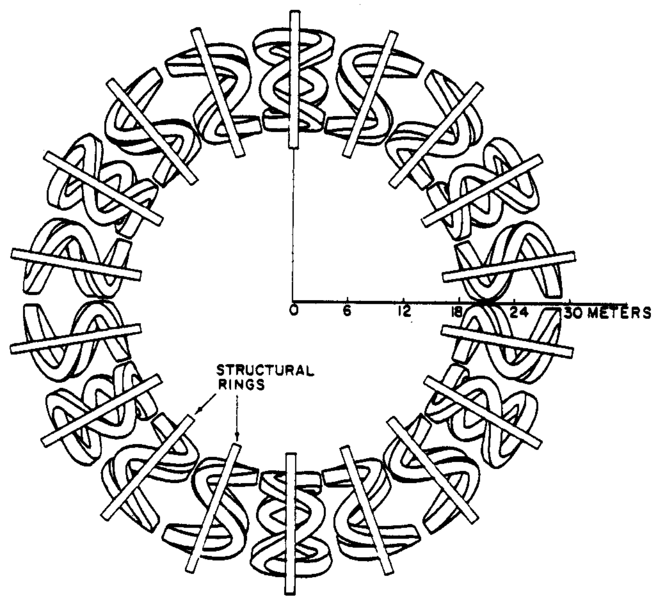


Fig. 1. Magnet Configuration of UWTOR/M.

TABLE I: Magnet design parameters for UWTOR-M.

Number of coils	18
Number of field periods	6
Number of coil types	2
Major radius	24.1 m
Minor radius	4.77 m
Total coil current	31.2 MA-turns
Central field	4.5 T
Peak field	11.6 T
Energy stored	171 GJ
Conductor current density	3333 A/cm^2
Maximum total force	144 MN/m
Net force/coil (inward)	200 MN
Mass of each coil	866 MT
Mass of support ring	309 MT
Virial theorem mass	127 MT

Magnetic Loads

Magnetic forces on the coils are calculated using the EFFI code [2]. These forces include the self force on an individual coil and the interactive force between adjacent coils. The force components F_R, F_P and F_T in the radial, poloidal and toroidal directions as well as the force magnitude F_M are shown in Fig. 2. All force components are given on a per unit length basis as functions of the poloidal angle ϕ. This convention along with a schematic representation of the force components are also illustrated. Summing the forces gives a net centering force of about 200 MN per coil.

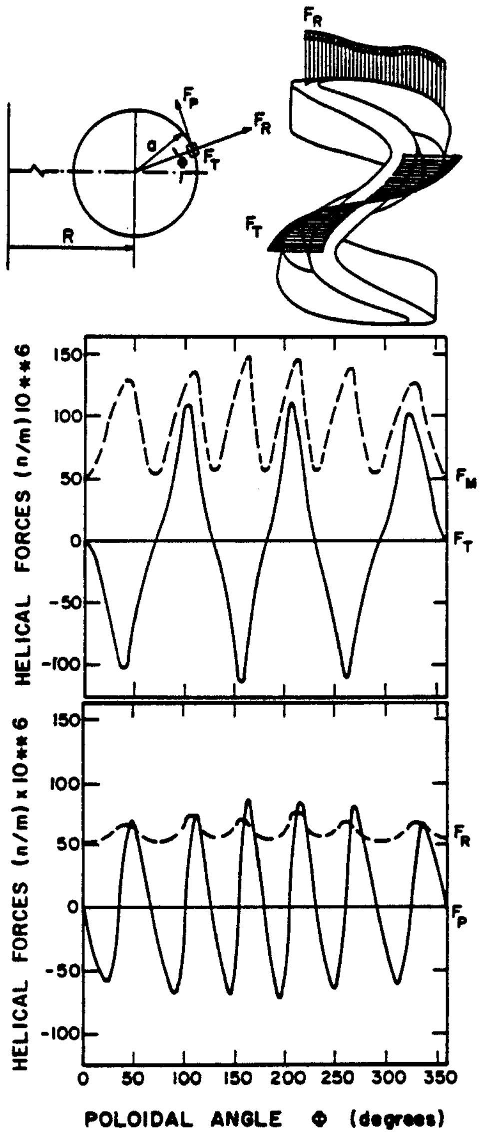


Fig. 2. Magnetic Force Components.

This force is reacted against a central structure through fiberglass epoxy struts.

Coil Support System

Inspection of the magnetic force distributions shows that the radial components of the force varies little with respect to the position. The toroidal component of the force reverses direction six times over the angular position of the coil and is concentrated at the bend corner regions where the coils come in close proximity. The poloidal component of the force shows greater frequency of inversion and has zero value at the corner regions of the coil.

Study of the force distribution has led to the coil support concept shown in Fig. 3. A reinforcing ring outside the coil case is used to resist the expansion due to the radial component of the force. The ring is welded directly to the outer surface of the coil case forming a coil-ring assemblage. The assemblage is

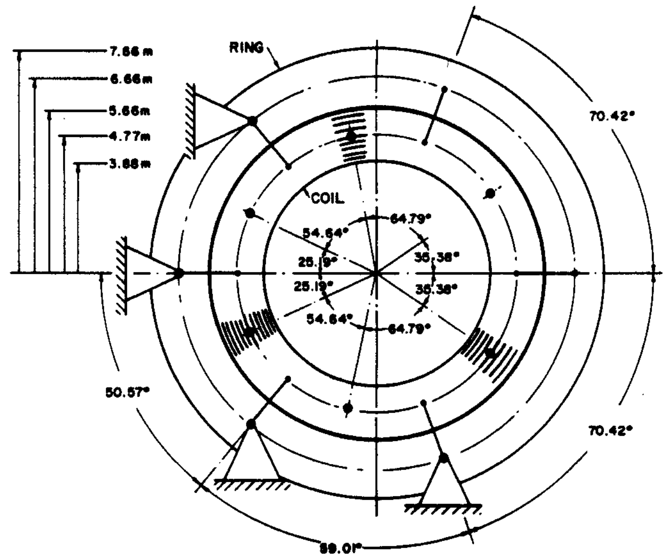


Fig. 3. Coil Support Concept.

mounted on the lower and central supports and attached to the neighboring coils. In the present design four hinge supports situated at the ring-case connections are used to transmit the central force to the foundation and central structure. No additional support is needed on the top and outer regions of the reactor. Removal and maintenance of the reactor coil modules can be achieved without interfering with adjacent coil-ring assemblies.

To achieve the cryogenic independence, separate dewars are required for each coil-ring assemblage. At the bend corners of each coil, contact inter-coil connections made of insulating structural material such as NEMA-G-10CR are used to counteract the mutual attractive forces. When the coil system is re-energized, the mutual attractive loads are released allowing the contact regions to separate sufficiently to remove one coil without disturbing its neighbor. Such design thus fulfills the full modularization of the coil systems.

The support system is also compatible with other reactor components. The space between coils and under the ring has enough room for the divertor target. Coolant and breeding material connections can be accessed in the rear of the coil.

Design and Analysis

The initial cross section designs of the coil case and reinforcing ring are shown in Fig. 4. To prevent the accumulation of the magnetic load, a central web is used to divide the coil case into two winding regions. A similar design is used for the reinforcing ring to stiffen the side walls. Stainless steel 304 LN-SS is chosen as the structural material for both the ring and coil case.

To have the designed field topology for the plasma, the maximum deformation of the coil is limited to 5 cm, or 0.2% of the major radius of the reactor [1]. The maximum induced stress in the coil structure is limited to 533 MPa, or two thirds of the yield stress. The

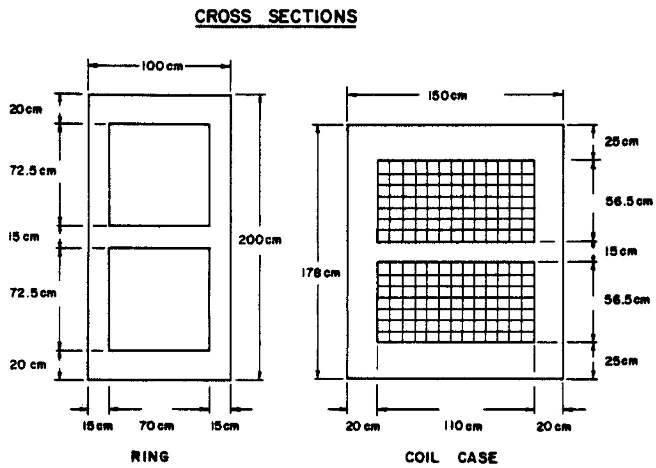


Fig. 4. Cross Section Design for Coil Case and Reinforcing Ring.

strength of the conductor is neglected in the study as a simplifying assumption except to the extent it transfers load to the coil case. The coil case is consequently designed to carry the entire magnetic load. This approach leads to a conservative, overestimated stress in the coil structure.

Finite element stress analysis has been carried out for the coil structure using the SAP4 code [4]. Interest of analysis is in determining the induced stresses in coil case and ring, the reaction forces, the forces at the connections between coil case and ring, as well as the interactions between neighboring coils. As an initial design study, detailed connection and support design are not included. Three-dimensional beam elements are considered sufficient for the present purpose of analysis.

The finite element model used includes 100 beam elements for each of the coil case and ring. The connections between them are modelled as six beam elements with large values of elastic constants. The contact connections between neighboring coils are simulated by six boundary elements normal to the side wall of the coil case. The ring is supported by four rigid joints as shown in Fig. 3. The finite element mesh for the coil case is made consistent with the EFFI magnetic force calculation model. The EFFI force results are input as distributed element forces into the SAP4 code.

The stress distributions over each cross section of the coil case and ring are recovered from the SAP4 results. The maximum values of the effective stresses over each cross section are then calculated and plotted in Fig. 5. Indicated also in the figure is the maximum deformation of the coil case occurring at the bend corner located at $\phi = 35.4°$.

The results in Fig. 5 show that except for the connection regions, the maximum stress levels in the coil case and ring are both below the allowable value. The narrow peaks in the connection regions result from the idealization of the connections as rigid beams and may be dismissed as caused by local boundary effects. The actual stress variations within these regions should be much lower due to the three-dimensional stress redistribution. The initial design for the coil case and

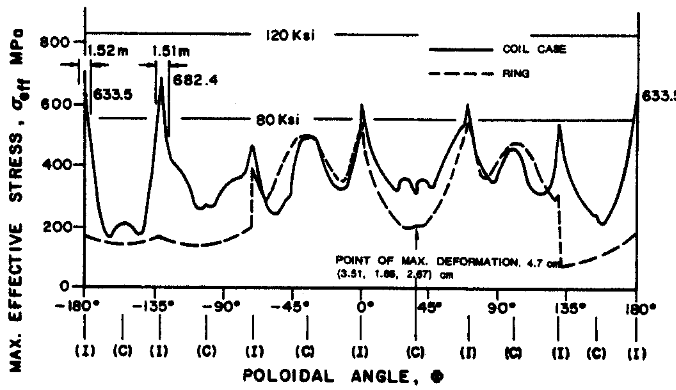
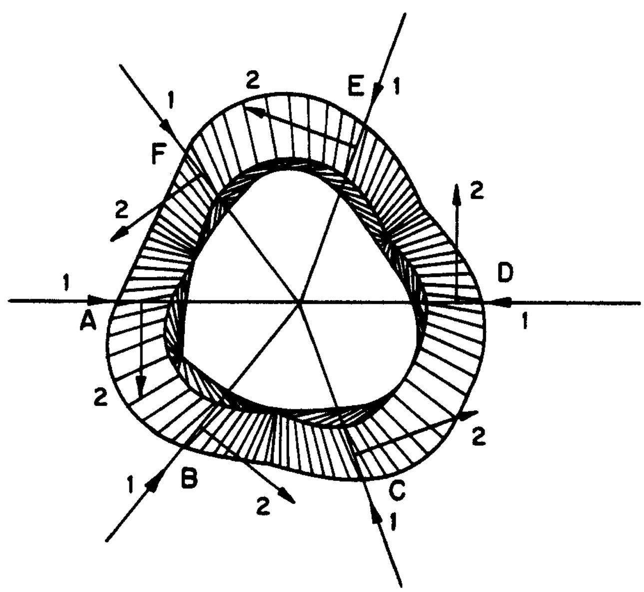


Fig. 5. Effective Stress on Coil Case and Ring.

ring, therefore, satisfies both the stress and deformation requirements.

Figure 6 shows the forces and moments at the ring-coil case connections in terms of local coordinate systems. The 1- and 2-axis of all the local coordinates lie on the radial mid-plane of the coil. The 3-



Connection	Force (MN)			Moment (MN-m)		
	F_1	F_2	F_3	M_1	M_2	M_3
A	293.0	59.6	31.7	-2.2	11.3	-39.7
B	283.0	-73.2	72.5	0.6	18.9	71
C	197.0	20.5	5.8	-0.5	-10.9	-43.1
D	178.0	-27.6	0.3	-20.2	-17.8	14.6
E	170.7	-37.3	-5.4	8.5	17.0	-8.1
F	228.6	5.8	34.1	-8.5	11.8	6.3

Fig. 6. Forces and Moments on Ring-Coil Case Connections.

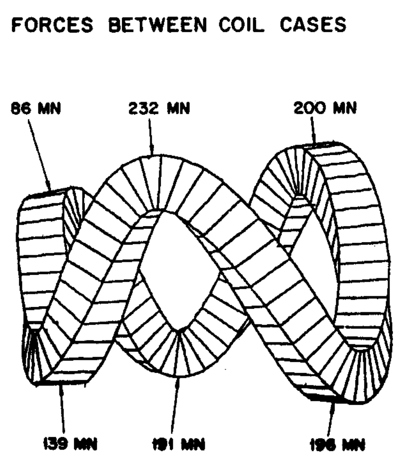


Fig. 7. Contact Forces Between Costs.

axis is defined by the right-hand rule and directed into the paper. The F_1 force components at all the connections are found to dominate. The ring, therefore, provides mainly a restraint to the radial expansion of the coil case.

The contact forces between neighboring coils are shown in Fig. 7. The directions of these contact forces are determined by the twisting of the coil case. Their magnitudes are roughly equal to the local toroidal forces in the corner regions. Under normal operations these forces balance for each coil.

Conclusions

The initial study of the UWTOR-M modular coil indicates that a credible design may be achieved to satisfy all the preliminary design objectives. Further studies will be needed for the structural and cryogenic details as well as the optimization of the present design. In terms of the coil mass per unit energy stored, the present design gives a structural mass of 787 MT vs. that of 127 MT required by the virial theorem. The ratio of 6.2 for the present design indicates a fairly efficient yet conservative magnet design [5].

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