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CONCEPTUAL DESIGN FOR A MODULAR STELLARATOR FUSION REACTOR MAGNET

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Summary

The present report summarizes the design of a modular stellarator fusion reactor UWTOR-M by the University of Wisconsin. The reactor configuration employs 18 twisted toroidal field coils with a major radius of 24.1 m, a minor radius of 4.77 m and a field of 5.5 tesla on axis. The total energy stored in the coil set is 190 GJ. A 10 kA monolithic conductor of NbTi/NbTiTa in copper has a design current density of 3200 Amp/cm^2 and an overall current density of 2045 Amp/cm^2 across the winding cross section. The conductor is bath cooled with pressurized superfluid helium to achieve high current density cryostability. The coil case is a stainless steel structure designed to withstand bending moments resulting from self force on the individual coil and the interactive force between adjacent coils. Force components in the radial, poloidal and toroidal directions are calculated for the individual coils using EFFI.[4] Typical values of the maximum force are 90, 100 and 120 MN/m. The net centering force on each coil is 245 MN inward. These loads are transferred through fiberglass composite struts to a room temperature central concrete column. A stress analysis is carried out on the coils in order to optimize the structural requirements.

Introduction

A steady state fusion power reactor design employing the stellarator concept (UWTOR-M) has been under study at the University of Wisconsin Fusion Engineering Program for the past year.[1] This alternative to the main line schemes of plasma confinement offers the advantage of steady state operation at ignition with no disruptions. Steady state operation eliminates the need for energy storage to drive the pulsed coils as in the tokamaks, thus reducing coil fatigue and simplifying blanket design. For such a reactor no ohmic heating, field shaping, or position control coils are required, which facilitates a modular approach to blanket and shield design. These factors do not eliminate the need for impurity control and ash removal. The modular coil configuration[1,2,3] is desirable for ease of blanket maintainability as compared to the continuous helices configuration of classical stellarators.

The present paper reviews the status of the magnet design for UWTOR-M. Iteration of design has produced a new set of optimized parameters that will satisfy the rotational transform requirements. With the present proposed design parameters the coil centering force is reduced by a factor of two, while continuing to permit access to blanket, shield and coil for maintenance. A schematic representation of the coil configuration is shown in Figure 1. The magnet parameters are listed in Table I.

UWTOR-M Magnet System

Forces

Magnetic loads are calculated using EFFI.[4] These include both the self force on the individual coils and the interactive force between adjacent coils. The force components F_r, F_p and F_T in the radial and poloidal

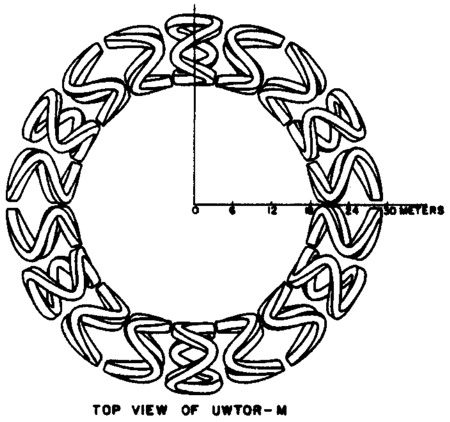
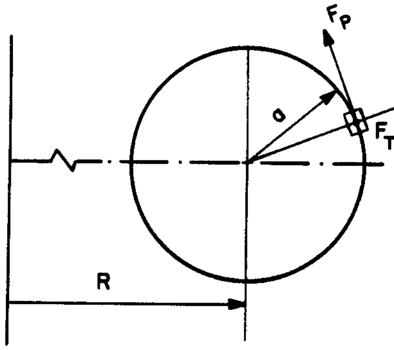


Figure 1 Schematic of coil configuration.

Table I
Magnet Design Parameters for UWTOR-M

Major radius	24.1 m
Minor radius	4.77 m
Total current	37 MA-T
Field on axis	5.5 tesla
Peak field	11 tesla
Energy stored	190 GJ
Average current density	2045 A/cm^2
Maximum total force	160 MN/m
Net force/coil (inward)	245 MN
Mass of each coil	1250 tons
Refrigeration requirements	
Struts (G10-CR)	0.6 MW
Leads	0.9 MW
Helium inventory	10^5 liters
Safety	
τ_D at 10 kV	30 sec
T_{max}	70 K
Final temperature for uniform energy deposition	110 K
Stray field at 100 m from reactor center	14 gauss

directions as well as the total force (F_M) per unit coil and toroidal length are plotted in Figure 2 as a function of poloidal angle (ϕ). Typical values of the maximum force are 90, 100 and 120 MN/m in the radial, poloidal and toroidal directions, respectively. The net centering force on each coil is 245 MN acting towards the reactor center. This load is transmitted to a central structure through fiberglass epoxy (Nema G-11 type material) support columns.



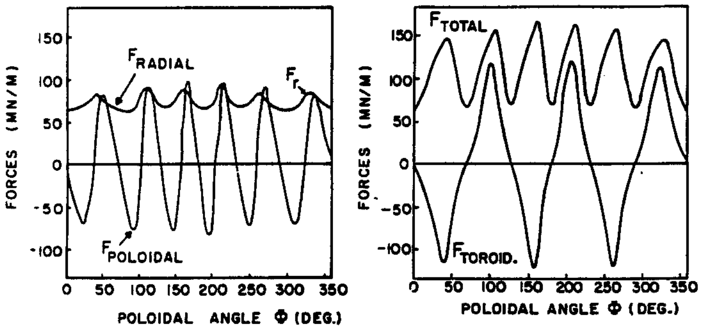


Figure 2 Magnetic loads as a function of poloidal angle ϕ.

Coil Design

The present magnet design achieves the goal of high current capability as well as mechanical rigidity and cryostability. As shown in Figure 3 the coil case is divided into two regions with current densities of 1650 and 2440 A/cm^2 in the high field and low field regions, respectively. The current density is divided in this manner to insure stability and to limit the maximum field on the conductor to about 11 tesla. Both winding regions are enclosed in a rigid stainless steel casing with a web separating them to prevent accumulation of the radial forces. The proposed conductor is a monolith of NbTi/NbTiTa in 3/4 hard copper stabilizer. The coil support system assumes the conductor only carries transverse loads to the stainless steel box and does not carry appreciable tension. The stainless steel box is consequently designed to carry the entire magnetic load.

The magnet cross section is made up of four components: stainless steel coil case, conductor, fiberglass epoxy insulation and liquid helium. The fractions of each component are listed in Table II.

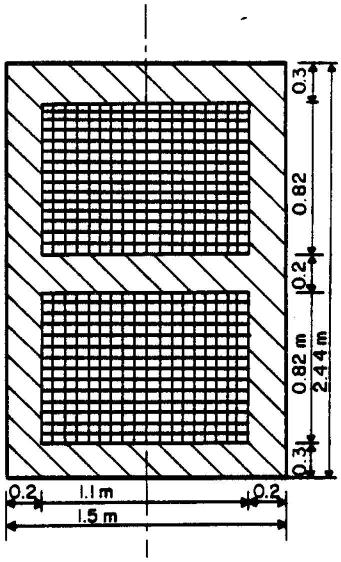


Figure 3 Schematic of winding cross section.

Table II
Design Features of Magnet Windings

Overall current density	2045 A/cm^2
Structure	3042N-SS
Max. stress	533 MPa (80 ksi)
Conductor current density	3200 A/cm^2
Current	10 kA
Inductance/coil	30 H
Number of turns	3700
Insulation	G10-CR
Volume cross section	
Stainless steel	51%
Copper (3/4 hard)	32%
Superconductor	1%
Helium	8%
Insulation	8%

The insulating spacers, Nema G-11 type material, are designed for load transfer between turns. Liquid helium is contained in cooling channels formed by the intermittent insulating spacers and conductors.

Construction of the coils for UWTOR-M would be similar to the Yin-Yang design for magnetic mirrors[5], with an added degree of difficulty. To maintain the conductor in places of negative curvature during winding, a special fixture would be required. A hydraulic ram could provide the force to conform the conductor to the coil contour. A coil clamping arrangement would then hold the conductor in place while the ram retracts to allow the next turns to be added.

Conductor Design

The absence of time varying magnetic fields in the stellarator concept allows consideration of a monolithic conductor design. Monoliths are beneficial for the ability to carry accumulated loads. A schematic representation of the conductor design is shown in Fig. 4. All four surfaces are intermittently cooled between insulating blocks covering 50% of the conductor surface. The channels formed by these spacers are filled with subcooled superfluid helium II. Any instability and associated heat generation must be transmuted through the helium channels. The specific design parameters of the conductor design are shown in Table III.

Based on the steady state stability criterion for superfluid helium II,[6] the present conductor design is conservative. The full load heat generation rate of 1.7 W/cm is well below the predicted stable heat generation of 2.5 W/cm^2. Thus, the average current density of 2045 A/cm^2 due to peak field limitations has a beneficial effect on stability.

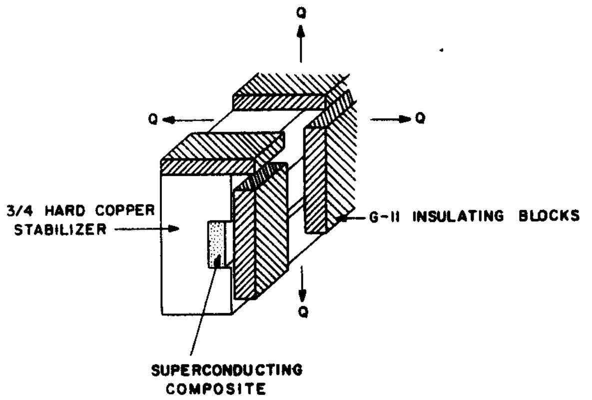


Figure 4 Schematic of conductor design.

Table III
Conductor Design Parameters

Conductor current density	3200 A/cm^2
Stabilizer	3/4 hard copper
Superconductor	NbTi/NbTiTa
Superconductor current density	1500 A/mm^2
Coolant	HeII-1.8 K, 1 atm
Heat generation (G/ℓ)	1.7 W/cm
Stable heat generation (Q/ℓ)	2.5 W/cm
Surface heat flux (q)	0.44 W/cm^2

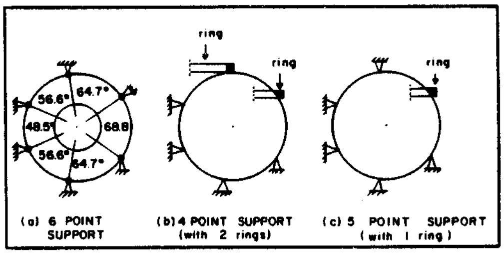
Major Refrigeration Loads

The coils are enclosed in separate dewars individually supported and shielded with multilayer insulation in vacuum. The net coil force is transmitted to the room temperature structure through G-11 CR fiberglass epoxy struts, 1 m long x 1.8 m^2 total cross section. The room temperature refrigeration required then is 0.6 MW, assuming that a liquid nitrogen heat intercept is used. The refrigeration power required for the current leads is estimated to be 0.9 MW based on 1ℓ/hr/1000 amp/lead. The total refrigeration capacity required is on the order of 1.6 MW.

Coil Support System

Because of the twisted nature of the coils, it is difficult to maintain the deformed shapes when loaded to the exact winding geometry. A displacement tolerance of .001 of coil diameter is the objective of the proposed support system.

Several schemes have been investigated to study the mechanical support of the coils to the applied magnetic force and gravitational load. A six point support scheme, two combined point support and toroidal ring systems are shown in Fig. 5. The toroidal rings are designed to resist the displacement of the supported points in the horizontal direction, but allow movement in the vertical direction. The stress analyses are carried out using the SAP4[6] code. Eighty-nine three-dimensional beam elements are used in all three cases. The calculated maximum displacement and effective stress for each support scheme are given in Table IV. The variation of the effective stress versus the poloidal angle for the six point support scheme is presented in Fig. 6. The stress level in a small localized region close to each support point is higher than the design value, but is still lower than the yield stress of the coil case material. Future efforts will be directed at reducing these stresses by iterating the coil case geometry at the support point. The final coil structure and support scheme is dictated by the engineering and economical considerations. It is realized from this preliminary stress analysis study that reinforced structural design for coils may be used to avoid elaborate magnet support systems. Possible choices of reinforcing schemes include reinforcing rings in the coil midplane and variable cross sectional design of the coil case. Work is in progress for determining the effectiveness of different reinforcing schemes and more detailed finite element modelling of the coil structure is being carried out.



(a) 6 POINT SUPPORT
(b) 4 POINT SUPPORT (with 2 rings)
(c) 5 POINT SUPPORT (with 1 ring)

Figure 5 Coil support schemes showing toroidal projections of the coils on the radial plane.

Table IV Maximum Displacement and Effective Stress

Support System	Displacement (cm)	Maximum Effective Stress (MPa)
a	1.3	768
b	4.0	1286
c	3.1	757

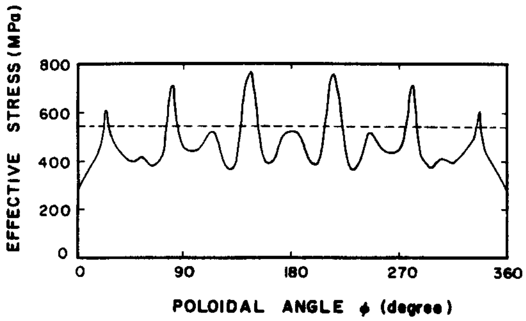


Figure 6 Effective stress as a function of poloidal angle for six point support scheme --- is design stress.

Conclusions

A new coil design for UWTOR-M with optimized parameters is proposed. The present design of the modular coils reduces the net centering force on the coils, prevents excessive buildup of radial forces and limits the peak field to 11 tesla. The use of 3/4 hard copper as a stabilizer provides satisfactory magnet stability. Several coil support schemes have been proposed and preliminary finite element stress calculations for a six point support scheme are presented.

References

1. I.N. Sviatoslavsky, S.W. Van Sciver, G.L. Kulcinski, D.T. Anderson, A.W. Bailey, J.A. Derr, G.A. Emmert, L. El-Guebaly, A. Khalil, J.L. Shohet, D.K. Sze, R.C. Sanders, and J. Tataronis, "UWTOR-M, A Conceptual Design Study of a Modular Stellarator Power Reactor", Proc. of 9th Symposium on Engr. Problems of Fusion Research", Chicago, Illinois, 1981.

2. S.W. Van Sciver, J. Derr, A. Khalil, and I.N. Sviatoslavsky, "Primary Magnet Design for a Stellarator Fusion Reactor", IEEE Trans. on Magnetics, Mag 17, No. 5, pp. 1703-1706, Sept. 1981.

3. "Modular Torus With Twisted Toroidal Field Coils", Princeton University, Plasma Physics Laboratory, Princeton, New Jersey, September 1979.

4. S.J. Sackett, "EFFI - A Code for Calculating the Electromagnetic Field, Force and Inductance in Coil Systems or Arbitrary Geometry", Lawrence Livermore Laboratory Report UCID 17621 (1977).

5. D.N. Cornish, J.P. Zbasnik, R.L. Leber, D.G. Hirzel, J.E. Johnston, and A.R. Rosdahl, "MFTF Test Coil Construction and Performance", IEEE Mag 15, p. 530 (1979).

6. S.W. Van Sciver, "Recent Development in He II Heat Transfer and Applications to Superconducting Magnets", proceedings of the Cryogenic Engineering Conference, San Diego, CA (1981).

7. S.J. Sackett, "User's Manual for SAP4 - A Modified Version of the U.C. Berkeley SAPIV Code", Lawrence Livermore Laboratory Report UCID-18226 (1979).

Acknowledment

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