Construction Techniques and Stress Analysis of Toroidal Field Magnets for Tokamak Fusion Reactors

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CONSTRUCTION TECHNIQUES AND STRESS ANALYSIS OF TOROIDAL FIELD MAGNETS FOR TOKAMAK FUSION REACTORS

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ABSTRACT

The toroidal field magnets which were designed for UWMAK-II (see Fig. 1), the second Tokamak Fusion Power Reactor studied at Wisconsin, are described, and loads developed due to out-of-plane forces on the toroidal field magnets are discussed. These loads which are produced by time varying fields from the transformer and vertical field magnets can be shared by the magnet windings, the liquid helium and vacuum dewars, and the lateral support structure between magnets.

In these designs the superconductive windings are embedded in solid forged stainless steel "D" shaped discs for maximum structural advantage [1]. A finite element analysis would be appropriate for a stress analysis of a final configuration but is not economically justified for use as a design tool. Instead, finite length segments approximating the "D" shaped magnets are treated as beams under distributed out-of-plane loadings.

Fiberglass-epoxy spacers, uniquely spring loaded, give lateral stability to the toroidal magnets against time varying fields and additional stand-off spacers provide lateral support in case of a fault condition [2]. A cast aluminum structure is provided to transmit the loads between magnets. This structure is also a secondary vacuum barrier, isolating the toroidal magnet enclosure from the reactor building.

INTRODUCTION

Different types of lateral supports for toroidal magnets have been provided or have been proposed. An external truss type structure is used in the Princeton Large Torus, PLT [3]. The top and bottom disc structures support the top and bottom of the circular toroidal field magnets by means of articulate pads which are in turn kept from rotating about the vertical central axis of the reactor by the external truss.

In the Wisconsin UWMAK-I design [4], warm support columns were planned to extend laterally between adjacent dewars of the toroidal field magnets. In normal operation the lateral forces due to transformer, vertical field and plasma currents are carried from the toroidal field magnets, through insulating struts to the vacuum dewar and into the warm lateral support columns. In case of a fault condition a detector would activate a cylinder-piston element in each support column which would elongate the columns, distort the elastic walls of the vacuum dewar and clamp each magnet with additional insulating stand-off struts.

A fusion power plant feasibility report by the Princeton Plasma Physics Laboratory [5] proposes to use large liquid nitrogen cooled fiberglass epoxy fault compression pads between dewars separated from the magnet by 0.5 cm gap. During a fault condition, the lateral motion of a toroidal field magnet would consist of the closing of the 0.5 cm gap, the elastic deformations of the fiberglass epoxy pads and the fault compression structure.

The design of the lateral support system for UWMAK-II, described in this report was developed with the idea of minimizing the lateral motion of the toroidal field magnets during a fault condition by the use of a passive lateral support structure instead of the active one, as proposed for UWMAK-I. The system also provides lateral support of the toroidal magnets against the normal out-of-plane forces encountered during reactor operation.

TOROIDAL FIELD MAGNET DESCRIPTION

The toroidal field in UWMAK-II [2] is provided by 24 identical modified constant tension "D" shaped magnets which produce 3.67 T at a radius of 13 m, the plasma center.

The design philosophy adopted is that of total reliability employing present day technology and materials with minimum extrapolation. Fully cryogenically stabilized conductors cooled with liquid helium pool boiling at 4.2 K are used. A multiple redundancy concept is applied in which enough safety is built in to increase reliability and longevity.

The toroidal magnets have a horizontal bore of 19 m and a vertical bore of 28 m (see Fig. 1). In cross-section, the magnet including the dewar is 152 cm wide and 135 cm deep.

In order to provide circumferential clearance between the backleg dewars of the toroidal field magnets so that modules of the blanket could be removed, it was necessary to extend the backleg of the "D" coils to a greater radius than in UWMAK-I [4]. A constant tension design throughout in this case would have produced a very tall and costly magnet. It was therefore necessary to deviate from the constant tension design in order to produce a modified "D" which is not any taller than that required to accommodate internal system components. To accomplish this, additional structure has to be provided to resist bending, and bracing from the central support structure must be extended over the non-constant tension portion of each toroidal magnet.

Figure 1 shows a cross-section of UWMAK-II. The constant tension portion of the magnet includes the backleg and extends both on top and bottom to a radius of 15 m. Forward from these points the magnets depth is increased to resist the bending and hoop stresses induced by the magnetic loading. In this region, the conductor size and spacing are the same as elsewhere but are kept to the inside edge of the magnet in order to minimize stresses and the stored magnetic energy.

The toroidal magnets are entirely supported on a massive stainless steel cylinder 4.75 m outer radius, 3.2 m inner radius, and 35 m high. This cylinder, called the central support structure, is built up of interlocking rings on which the transformer coils are wound. As the rings are assembled on top of each other, they are bolted together and

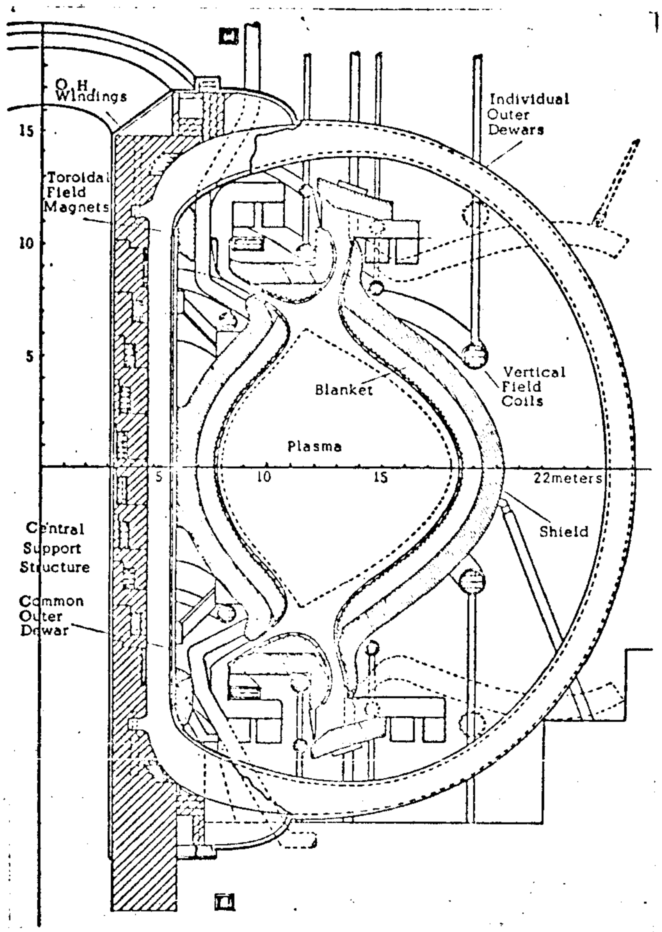

Fig. 1. Cross-section of UWMAK-II.

circumferential welds seal the interface to the outside. Channels will be provided to allow liquid helium to circulate through the cavities making the central structure, in effect, an inner dewar at 4.2 K.

An important feature of the non-constant tension design is the fact that the horizontal components of the magnetic field no longer balance the tension in the backleg as a result of which, the upper and lower nearly horizontal portions of the toroidal magnets exert a large radial outward force on the central support structure. The magnets are attached to the central support structure by means of pins interlocking it with a support beam mounted at the top and bottom of each magnet. Pins subjected to shear on several levels are needed to restrain the magnets against the radial outward force.

Each magnet is composed of 19 extended "D" shaped stainless steel washers 5 cm thick and 98 cm deep. These washers, henceforth referred to as discs, will have grooves forged in both surfaces. The conductor which is an OFHC copper backing strip soldered to a composite strip of OFHC copper matrix containing twisted TiNb filament is insulated with fiberglass epoxy tape and rolled with liquid epoxy into the grooves on both sides of each disc. The conductor width is tapered such that the high field end contains more copper and superconductor than the low field end. After the epoxy undergoes a final curing, the insulation facing out of the disc is machined off exposing the copper for cooling in a liquid helium bath.

The discs are separated from each other by micarta spacers, as shown in Fig. 2 and are then bolted with prestressed aluminum bolts which provide the shear restraint needed for handling the magnets during assembly and erection, and which maintain the stack tight in spite of the greater thermal contraction of the micarta spacers. A section of the assembled magnet is shown in Fig. 3.

Electrical connections are made at the top of each magnet. The conductors spiral toward the inner radius along one side of a disc, then emerge to the other side and spiral out to the outer radius. Splices between individual discs provide electrical continuity throughout the rest of the magnet.

The magnets are normally operated with 19 discs at a current which is about 26% less than the stability limiting value and carry an electromechanical load designed for 17 discs only. If two adjacent discs are disabled by an arc or some other reason, they can be disconnected by the electrical leads which extend from the discs at the outer surface of the magnet near the helium port. If further problems arise, a second pair of discs can be disconnected without exceeding the allowable stress or current density in the remaining discs.

Each toroidal magnet is surrounded by its own inner dewar which is the liquid helium barrier. The inner dewar is rectangular in cross-section as shown in Fig. 3, is made of 0.32 cm thick stainless steel, and is separated from the discs by insulators.

The straight legs of the magnets are surrounded by one continuous outer dewar consisting of a heavily reinforced stainless steel cylinder subtending the magnets in the toroidal direction. Individual outer dewars branch off at the top and bottom to cover the curved portion of the magnets. Fifteen centimeters of superinsulation will be used wherever the inner dewar is in the radiation field of the outer dewar.

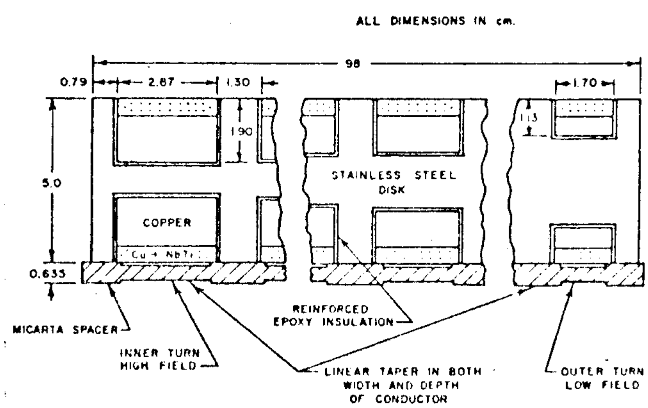

Fig. 2. Detail of toroidal field magnet disc.

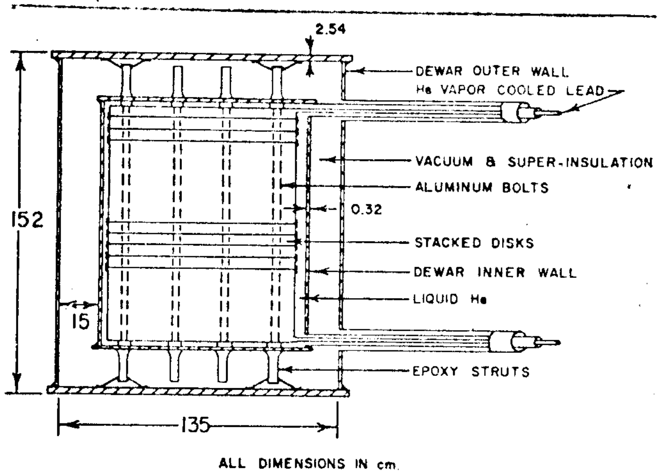

Fig. 3. Assembled toroidal field magnet and dewar.

LATERAL SUPPORT AND STRUCTURAL SAFETY

A significant change was made possible in the lateral support of the toroidal field magnets when the decision was made to provide a secondary vacuum wall (Fig. 4) at the location of the toroidal magnet dewar instead of the wall of the reactor room. The lateral support structure designed for loads developed during a fault in the toroidal magnet system is entirely adequate to carry the vacuum load as well as the normal operating loads imposed by the vertical fields.

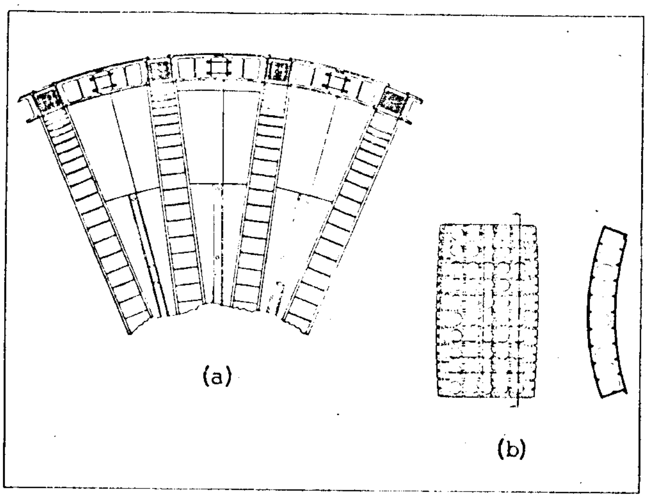

Fig. 4. (a) Lateral support structure, (b) Details of single shell panel.

In an attempt to provide an adequate design against catastrophic failure of the toroidal magnet system, a preliminary examination of various modes of failure was made. Although it is conceivable that several adjacent toroidal field magnets could simultaneously experience a complete loss of current in a matter of a few minutes, the decision was made not to design the shell structure between magnets to withstand this condition without permitting large deformations. This decision was prompted by the assumption that such an occurrence would in all probability be caused by an accident which would render useless the toroidal field magnets involved and would necessitate their removal. In this event, the replacement of the vacuum shell walls and the penetrations through the walls in the area involved would also be possible. The savings in repair costs which might occur if a heavier shell were used would be more than offset by the added cost of the heavier wall. The cost effectiveness of such a decision will have to be undertaken eventually.

The first failure mode considered is a case in which the current in a single toroidal field magnet is assumed to drop to some low value in less than three or four minutes. The lateral support structure is designed such that this will not cause excessive deformations or motions of the magnets or dewars. A second failure mode for which design calculations were carried out is one in which two adjacent toroidal field magnets suffer a loss of current simultaneously. In this instance, the design permits relatively large motions of the dewars but keeps the stresses low enough to assure that no permanent deformation takes place in the magnets, dewars and the vacuum wall.

The following sections will describe in some detail the design process used for the support shell between the toroidal field magnets.

Design requirements based on the failure of one toroidal field magnet.

If the current in a single toroidal field magnet drops rapidly due to some unforeseen mode of failure, the nearby magnets will experience an increase in current because of their inductive coupling to the failing magnet. Table 1 gives a list of the changes in current, $-\Delta I_k/I_1$, produced in the 24 magnets which comprise the toroidal field system. Magnet number 1 is the magnet which is assumed to

Table 1

Induced Currents in the Toroidal Field Magnets and Shell Stresses and Circumferential Motions of the Dewars Due to the Failure of Magnet Number 1

Magnet No. k		$-\frac{\Delta I_k}{\Delta I_1}$	$\frac{F_k}{F_o}$	$\frac{\Sigma F_k}{F_o}$	Lateral Compressive Shell Stress (N/cm^2)	Lateral Dewar Motion (cm)
1		-1	0			0
				0	0	
2	24	0.2571	1.14			10.34
				1.14	6920	
3	23	0.0336	0.19			9.68
				1.33	8670	
4	22	0.0224	0.13			8.89
				1.46	8860	
5	21	0.0147	0.10			8.05
				1.56	9460	
6	20	0.0110	0.08			7.14
				1.64	9950	
7	19	0.0088	0.06			6.17
				1.70	10310	
8	18	0.0075	0.04			5.18
				1.74	10560	
9	17	0.0066	0.03			4.17
				1.77	10740	
10	16	0.0061	0.02			3.15
				1.79	10860	
11	15	0.0057	0.01			2.11
				1.80	10920	
12	14	0.0055	0.01			1.07
				1.81	10980	
13		0.0054	0			0

be failing. In addition, Table 1 lists the relative magnitudes of the lateral forces, F_k/F_o, acting on each magnet caused by the distortion of the toroidal field as well as the summation of these forces, $\Sigma F_k/F_o$, which create the shell stresses given in the following column. The last column of data indicates the lateral motion of the outer leg of each dewar at the midplane of the magnet. The force F_o is the nominal repulsive force between two parallel conductors, each of which is carrying a current I_o and spaced apart a distance of S meters.

$$F_o = \frac{2(10^{-7}) I_o^{\,2}}{S} \text{ Newtons/meter} \qquad (1)$$

I_o is taken equal to the normal operating current carried by each toroidal field magnet and equals 10^7 amperes. The current change in the failed magnet, ΔI_1, is taken equal to the negative of I_o.

The force, F_k, is the lateral magnetic loading per unit length on each magnet and the sum of all F_k from magnets 2 to i is the accumulated lateral load which must be carried by the shell structure between the dewars of magnets i and i + 1. There are no tensile forces between the dewars for coils 2 and 24 since the shells are provided with unidirectional slip joints as described later.

Design requirements based on the failure of two adjacent toroidal field magnets.

It is reasonable to expect the sizeable increases shown in Table 2 for the induced current and lateral forces caused by the simultaneous failure of two adjacent magnets. Those magnets which are adjacent to the two disabled display an increase in the induced current of less than twice that occurring for a single magnet failure due to the decreased coupling with the second failed magnet. As before, the magnets nearest the failed magnets show the greatest lateral motion.

Design of lateral support shell.

The lateral motions of the dewars could be reduced appreciably if provisions are made for the shells to carry tension in a lateral direction and the attachment between the shells and the dewars is made strong enough to carry this tensile load. We chose not to do this since tensile stresses developed over the much shorter lateral span between magnets 2 and 24 in Table 1, or between magnets 2 and 23 in Table 2, would be much larger than the compressive stresses indicated. A system capable of carrying the loads in tension would require more structure and would be more costly and difficult to design. To allow for the lateral dewar motions without developing tensile stresses in the shells, a spring-loaded slip joint is provided at the centerline of each shell as shown in Fig. 4. This slip joint is provided with O-ring type seals just as are the joints between the shells and the dewars. The slip joints will have interlocking lateral lugs to provide the shear resistance necessary to carry the torsional loading created by the polodial fields.

Since the lateral forces due to the field distortion vary inversely as the distance between magnets and this distance in turn varies almost directly with the radial distance from the central toroidal axis, the wall thickness and the reinforcing rib areas of the shell shown in Fig. 4 vary inversely as the radius. This keeps the compressive stress in the shell structure as nearly constant as possible which in turn holds constant the circumferential unit strain. Under these conditions, the radial plane of each magnet remains essentially plane as it moves laterally. Modifications in this distribution of material are made near the central support structure to compensate for the different circumferential stiffness of the core as compared to the shell. The purpose of the above described procedure is to minimize the lateral bending strains in the magnet.

Table 2

Induced Currents in the Toroidal Field Magnets and Shell Stresses and Circumferential Motions of the Dewars Due to the Failure of Two Adjacent Magnets

Magnet No. k		$\frac{\Delta I_k}{\Delta I_1}$	$\frac{F_k}{F_o}$	$\frac{\Sigma F_k}{F_o}$	Lateral Compressive Shell Stress (N/cm^2)	Lateral Dewar Motion (cm)
1	24	-1.00	0			3.11
				0	0	
2	23	0.40	2.06			18.65
				2.06	12500	
3	22	0.09	0.43			17.45
				2.49	15100	
4	21	0.05	0.28			15.99
				2.77	16800	
5	20	0.03	0.20			14.38
				2.97	18000	
6	19	0.02	0.16			12.65
				3.13	19000	
7	18	0.02	0.12			10.82
				3.25	19700	
8	17	0.01	0.08			8.93
				3.33	20200	
9	16	0.01	0.06			6.99
				3.39	20560	
10	15	0.01	0.04			5.01
				3.43	20800	
11	14	0.01	0.01			3.01
				3.44	20870	
12	13	0.01	0.01			1.01
				3.45	20900	

The ribbed radial edges of the shell panels which are adjacent to the dewars provide the bending resistance needed for the sidewalls of the dewars which are loaded laterally from the many fiber-reinforced epoxy struts shown in Fig. 5. The perforations in the outer shell wall are needed for core removal and inspection. They are designed to permit the use of constant wall thicknesses throughout a given section to assure sound castings. They also provide reduced stiffness for the outer wall in proportion to the lower lateral load as compared to that on the inner wall.

Dewar design.

To transmit the circumferential load from shell to shell through the inner and outer dewar walls requires that these walls carry the compressive stresses across a length of 152 cm without suffering any buckling. To accomplish this for the maximum load of 3.45 F_o requires that the inner dewar wall be 2.54 cm thick at midplane of the outer leg of the magnet and be braced with lateral ribs spaced 1 m apart along the length of the dewar. Each rib at midplane is 5 cm in width and tapered in height from 2 cm at the ends to 10 cm at midlength.

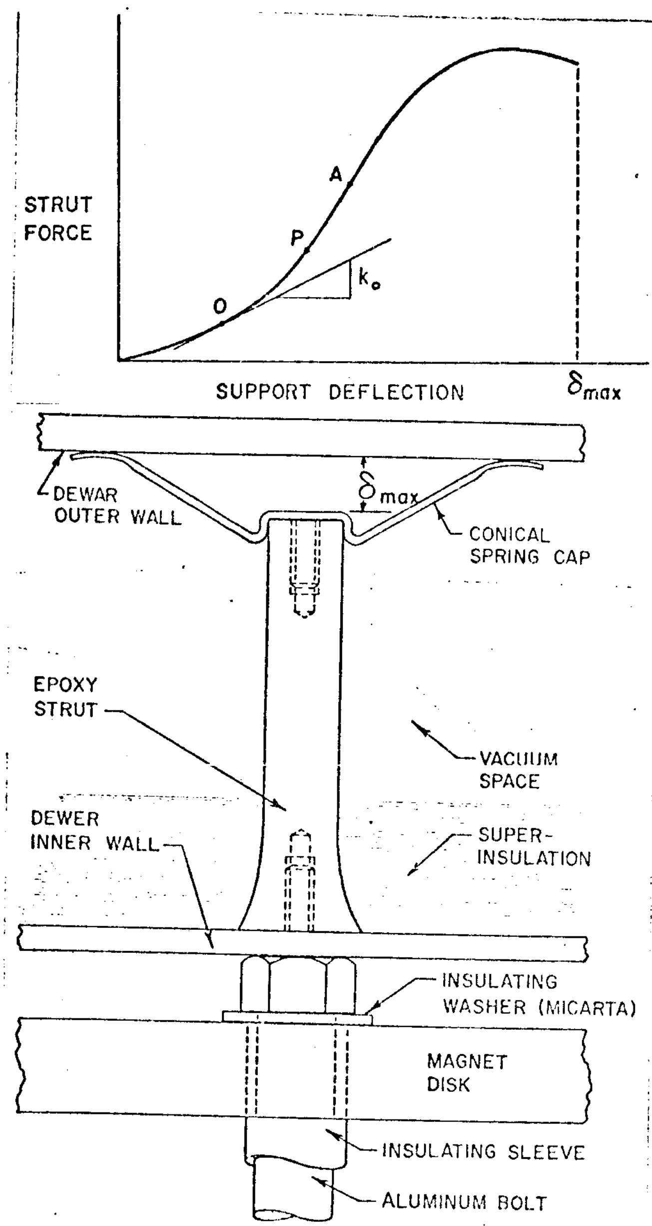

Fig. 5. Lateral support strut showing load deflection curve.

As the dewar major radius (distance from the central axis of the toroid) decreases, the wall thickness and the rib thicknesses must be increased as was discussed for the shell thicknesses.

Similarly the outer dewar wall would be 1.38 cm thick at midplane and be ribbed every 1 m with ribs 3 cm wide and 8 cm deep at midlength. These dimensions would also be increased as the major radius decreases.

The dewar side walls are 2.54 cm thick at all radii since the major loading is carried by the ribbed shell walls.

Dewar strut design.

The lateral loading on the dewar side walls is transmitted from the inner helium dewar to the outer vacuum dewar by the fiber-reinforced epoxy struts shown in Fig. 5. Sufficient struts are provided to transmit the fault load on magnet 2, which is 2.06 F_o, but they cannot be in contact with the outer dewar wall during normal operation without causing an excessive heat leak into the magnet. Therefore, ten percent of the struts are provided with a nonlinear conical spring cap as shown in Fig. 5. The remainder will be the same strut without the cap and will have a clearance of approximately 1 cm from the outer dewar wall.

The design of the conical spring cap must provide for several functions:

(1) The effective spring constant must provide the proper centering forces when the dewar is assembled (see point A on Fig. 5) and maintain these forces when the magnet is cooled. The spring constant k_o must be large enough to provide for the magneto-elastic stability of the toroidal field magnets under their own radial field forces but at the same time, not be so large as to create excessive friction from the motion of the toroidal field magnets relative to the outer dewars. This spring constant is illustrated at the operating point O in Fig. 5. During cooldown the inner helium dewar moves relative to the outer vacuum dewar. This motion is comprised of two parts; parallel to the struts the relative motion is taken up by the spring cap as it moves along the operating curve from point A to point O. At right angles to the strut, the relative motion during cooldown is approximately 8 cm. When the magnets are energized to full current, this latter motion reverses and it moves back approximately 3 cm. The materials used for the conical spring cap must, therefore, have a low coefficient of friction against the smooth stainless steel dewar wall. A suitable lubricant compatible with a vacuum environment will be used.

(2) The conical spring caps must be designed to provide a larger spring constant when the toroidal field magnets move laterally under the forces from the poloidal fields (see point P in Fig. 5). Since the poloidal fields will rise and fall every 90 minutes during a burn cycle, any magnet motion will be accompanied by stresses which are cyclic in nature and will be of concern regarding fatigue. Furthermore, the loads from the poloidal fields must not cause the stand-off struts to make contact. Fortunately, there will be no displacements causing friction forces to develop when the lateral loads due to the poloidal fields are imposed.

(3) The conical spring caps must not overload the struts on which they are mounted when a failure condition occurs such as the loss of one or two toroidal field magnets as was previously discussed. Under this condition, the force in the conical spring cap will reach a peak and decrease slightly as all of the stand-off struts move into contact. The proposed shape of the conical spring cap should accomplish this goal.

Design requirements for the torsional loading produced by the poloidal fields.

The poloidal fields produced by the currents in the vertical field coils, transformer coils and the plasma produce lateral forces on the toroidal field magnets. To evaluate these forces, the lateral force on each 1 meter segment of a toroidal field magnet was determined using the current vectors in the toroidal field magnet and the field lines due to the combined divertor, transformer and plasma currents when they are all at their maximum values [2]. Later studies will evaluate the effects of different combinations of currents which occur during a burn cycle. Table 3 lists the lateral forces on each given segment which are numbered from the midplane. These forces are also shown in Fig. 6. The forces are antisymmetric being equal in magnitude but opposite in direction above and below the midplane. The torsional shear stresses listed in Table 3 were calculated from expressions based on the following observations. 1) Due to the antisymmetry just described, there is no lateral motion at midplane of the structure made up of the central core, magnets and dewars and the lateral support shells. This is true at midplane both in the inner core and at the midpoints of the outer legs of the magnets. 2) If one examines the loads on one segment only of each magnet, for example, segment number 11, one finds that there are 24 loads of 1,175,000 N acting clockwise around the upper half of the toroid and a similar set of forces acting counterclockwise around the lower half. These line loads would be resisted by shear stresses in two paths, one over the 22 meters between the upper and lower line loads around the outer portion, and the other over the longer path over the top and down through the central core. The proper division of the line load between these two paths is found by noting that the total shear deformation must be the same over both paths. This is done in turn for all of the lateral forces shown in Fig. 6 and Table 3.

Superimposing the results for each lateral load using the shell dimensions given previously produces the stresses and the circumferential motion at each section as listed in Table 3. The shear stresses are seen to be small. Bending resistance of the toroidal field magnets and dewars are negligible serving only to distribute the lateral loading smoothly to the shell. From the curvatures associated with the circumferential motions of the dewars, maximum stresses of no more than 1500 N/cm^2 would be developed in the dewars or magnet discs.

The actual lateral motion of a toroidal field magnet would be found by adding to the dewar motion the deformation of the conical spring caps, no more than 0.25 cm, and a strut deformation of approximately 0.02 cm. These extremely small lateral motions, which are common to all 24 magnets, will not appreciably modify the toroidal fields.

SECONDARY VACUUM REQUIREMENTS

There are some very good arguments for providing a secondary vacuum for the plasma toroid. In UWMAK-II the lateral support structure for the magnets is used to provide a secondary vacuum in the

Table 3

Shear Stresses with Shell Wall and Circumferential Motion of Dewar Walls on the Toroidal Field Magnets due to Maximum Combined Poloidal Fields From Divertors, Transformers and Plasma

Section Number	Lateral Force on Magnet N/m	Shear Stress in Shell N/cm^2	Circumferential Motion of Dewar cm
1	-38,150	-1250	-.052
3	-89,170	-1290	-.160
5	216,200	-1240	-.266
7	858,000	- 890	-.350
9	1,310,000	- 270	-.386
11	1,175,000	360	-.369
13	648,000	750	-.312
15	89,200	870	-.241
17	-432,400	720	-.176
19	-503,200	460	-.132
21	-58,500	365	-.101
23	25,200	369	-.070
25	3,580,000	1522	.020
27	5,163,000	880	.025
29	-12,200,000	-190	.020
31	-1,430,000	-390	.010

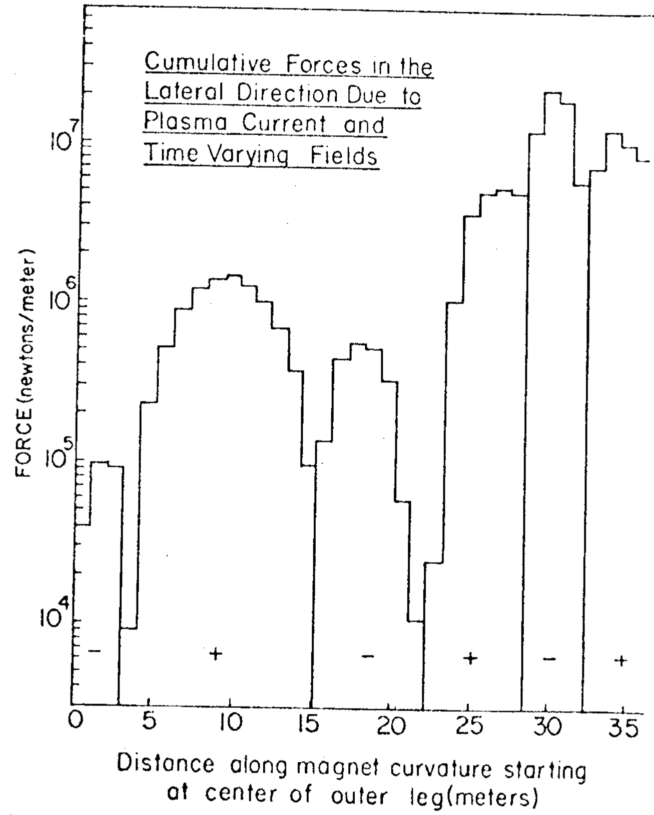

Fig. 6. Cumulative forces in the lateral direction due to plasma current and time varying fields.

toroidal magnet enclosure. This reduces leakage to the primary vacuum zone of the plasma region, alleviates the danger of a lithium fire and prevents tritium leakage into the reactor building.

A major problem associated with using the lateral support shell as a vacuum wall is the need to decouple the motion of the shell from the penetrations which are required for the support of components within the toroidal enclosure. In order to do this, the design has to accommodate two functions. (1) Individual sections of the shell must be capable of separating in the middle while under tension without imparting forces on the component supports and without breaking the vacuum seal. (2) Individual sections of the shell must have the capability of being displaced in the toroidal direction without separating while in compression, also subject to the above restrictions.

Upper and lower shell panels, reaching 20 m in the radial direction from the center of the reactor will have penetrations in them but need not be removable for access to the blanket and shield regions. In addition, twelve panels along the central plane will have neutral beam and fueling ports.

The penetrations will be attached to plates which will be fixed at all times. These plates will fit in both halves of the shell panels and be sealed to them with conventional "O" rings. The fit will be such as to allow the panel halves to separate under tension while the penetration plate remains stationary. Similarly, under compression, the panel can be displaced toroidally in either direction without moving the penetration plate. Bellows will be used to attach the penetration to the plates to allow for relative motion between them. Each shell panel will be electrically isolated from the dewars and adjacent panels in order to reduce the shielding effect on the changing poloidal fields.

EXPERIMENTAL PROGRAM

The University of Wisconsin is currently undertaking an experimental program for testing some of the ideas proposed in the current design. These ideas represent a fair departure from conventional superconductive magnet design.

The initial phase of the experiments will consist of testing a copper conductor imbedded in a circular stainless steel disc. The conductor will be insulated in the same way as proposed for the UWMAK-II design and will be imbedded in both sides of the disc. Subjecting the disc to cyclic tensile loading at 4.2 K will determine the degradation of the electrical conductivity of the copper as well as the integrity of the insulation and the epoxy bond. Careful measurement of the strains in the conductor and the disc will be made to establish a relationship between cyclic strain and electrical conductivity.

Future experiments involving testing of superconductive materials in copper matrices also imbedded in stainless steel discs are planned. These experiments can be expanded to the study of heat transfer, current density and normal transition.

SUMMARY

In summary it must be said that alternate methods for building large superconductive magnets for fusion reactors such as the proposed embedded conductor scheme should be thoroughly investigated.

The lateral support structure should be an important part of the overall design in a fusion reactor toroidal magnet system. The failure of several adjacent magnets can be handled without permanent damage and at reasonable cost. It appears that a secondary vacuum barrier can be easily incorporated into the lateral support system.

ACKNOWLEDGEMENT

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