UCRL 15291

P.O. 6419309

final report

Sept 1979-Aug 1980

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STRUCTURAL SUPPORT CONCEPTUAL STUDIES FOR A YIN-YANG MAGNET OF A TANDEM MIRROR REACTOR

GRUMMAN AEROSPACE CORPORATION

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final report
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STRUCTURAL SUPPORT CONCEPTUAL STUDIES FOR A YIN-YANG MAGNET OF A TANDEM MIRROR REACTOR

prepared for
Lawrence Livermore Laboratories

Under Purchase Order 6419309

by
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July 1980

FOREWORD

The Lawrence Livermore National Laboratory (LLNL) of Livermore, California contracted with the Grumman Aerospace Corporation through Purchase Order 6419309, dated August 1979, to have provided to them level of effort engineering support services in accordance with Appendix A - Scope of Work, Task 2. The design work was performed at LLNL and the structural analysis work was performed at Grumman Aerospace, Bethpage, N.Y. The work was performed under the authorization of Mr. R. Botwin, Assistant Director of Advanced Energy Systems at Grumman. Dr. G. Carlson was the LLNL technical monitor for this task.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. G. Carlson of LLNL for his useful discussions during the course of this study. They are also grateful to Mr. J. Myall of LLNL for obtaining the electromagnetic loads and critiquing the work. The authors also wish to thank Mr. I. Zatz and Miss M. Penn of Grumman for their assistance with portions of the computational effort involved in this study.

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1 - INTRODUCTION AND SUMMARY

Magnetic systems of tandem mirror fusion reactor (TMR) designs have employed Yin-Yang coils (see Figure 1-1) near the ends of a central cell, to help confine the plasma. Because of extremely high magnetic field requirements, conceptual designs of mirror power reactors have historically used high-field magnets and massive restraining structures (see Refs. 1 and 2) to support the electromagnetic loads. Recently, however, application of the thermal barrier concept to tandem mirrors (Ref. 3) has improved reactor performance sufficiently such that a Yin-Yang end-plug magnet may not require significantly higher technology than is required for the Mirror Fusion Test Facility (MFTF) Yin-Yang coils (Ref. 4), which simply employ the coil cases and integral stiffening between the pair of coils.

Fig. 1-1 Yin-Yang Magnet Windings

The purpose of the present study was to determine whether the TMR Yin-Yang coils will require the elaborate external structural restraints employed in earlier mirror reactor studies (see Figure 1-2). The approach taken in our study was to use a simple coil case of compact design and to add and modify structural members to transfer loads from one coil to the other. It has been assumed that the magnet assembly will resemble the MFTF design (see Figure 1-3). The structural material

a. C-Clamps

b. External beam support structure

c. Prestressed concrete monolith structure

d. Internal coil support system

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Fig. 1-2 Four Solutions to the Problem of Carrying Large Lobe Spreading Forces

selected is 304 LN stainless steel with a yield stress of 120 ksi at 4°K. The niobium/titanium conductor is assumed to be of square cross-section to allow winding in two planes.

Fig. 1-3 MFTF Yin-Yang Coil Pair

This report contains a comprehensive summary covering work performed by Grumman Aerospace Corporation, in conjunction with the Lawrence Livermore National Laboratory, on the TMR Yin-Yang coils. The Yin-Yang coil pair used for our analysis has a major arc radius of 2.7 m and a minor arc radius of 1.18 m, compared with 2.5 m and 0.75 m for the MFTF (see Table 1-1). The maximum field on the present conductor is 9.04 Tesla. This magnetic field is created by, and interacts with, a conductor current which produces a 360 million Newton total force, tending to separate the parallel lobes of the major arcs.

TABLE 1-1 COMPARISON OF COIL PARAMETERS: MFTF VS. TMR

Parameter	MFTF	TMR
Major Arc Radius	2.5m	2.7m
Minor Arc Radius	0.75m	1.18m
Conductor Cross-Section	0.9m x 0.36m	2.1m x 0.36m*
Coil Section Current Density	2525 A/cm ²	2330-2500 A/cm ² **
Maximum Conductor Field	7.68 Tesla	9.04 Tesla
Lobe Spreading Force	100 x 10 ⁶ Newtons	360 x 10 ⁶ Newtons
Mirror Length	3.6m	4.9m
Vacuum Center Field	2T	4T
Mirror Ratio	2.1	1.5
Conductor Wt (both coils)	54,430 kg	201,000 kg
* increased to 2.1 x 0.44m at center of minor radius ** 2330 A/cm² for inner coil, 2500 A/cm² for outer coil R80-1194-024P		

Section 2 describes the design considerations which were evaluated to establish the feasibility of supporting the coils in ways that facilitated functional requirements, while reducing peak stress levels. Section 3 defines the 1/4-coil finite element thin beam structural model used in the analysis, while Section 4 presents the results of our analyses. The effects of inter- and intra-coil supports were determined as well as continuous beam interconnections between coil cases. Support stiffnesses were varied and their effects assessed as well.

The results of this study are concluded in Section 5, where recommendations are made regarding further work in the area of structural support and design of Yin-Yang magnets.

2 - STRUCTURAL DESIGN CONSIDERATIONS

As will be described in Section 4, the region of highest stress in the coil case has generally been found located near the center of the minor arc. This peak stress is most often caused by in-plane bending, as the larger lobe separating forces are carried by moments in the minor arc. Thus, from a purely structural point of view, the optimal way to reduce this stress is by directly connecting the major radii of the same coil together with intra-coil stiffening structure. However, because the plasma fan spreads rapidly as it leaves the major arc of the coil pair, this load path is not available for the placement of support structure. In addition, since the superconducting coil structure must be maintained at 4°K and the plasma heating of the first wall is very intense, a thermal/radiation shield of the order of 50 cm thickness is required between them, which further restricts this region for structural stiffening. Figure 1-2d shows an attempt to circumvent this problem by a "selected plasma leakage" design concept. For the TMR application, we have neither considered this nor any intra-coil structure approach to be feasible. However, several NASTRAN finite element structural analysis runs, described in Sections 3 and 4, were run to demonstrate the effectiveness of this latter method of support.

An initial set of NASTRAN runs was used to get a feel for the behavior of the structural support concepts by varying the use of inter- and intra-coil structure. Assuming a uniform 4-in. case thickness as a basis, eight support variations were examined. In all cases, the maximum stresses occurred in the small radius. We started with four inter-coil connectors (gussets) for the entire coil pair, one at the center of each arc.

This represented the minimum number of such supports considered for the entire coil pair. The stiffness of these gussets did not significantly affect the maximum stress level which was predominantly due to in-plane bending. We then located such gussets at 15°, 12°, and, finally, 3° intervals of arc. Distributing the inter-coil supports around the coil made the coil pair behave quite differently. Although the maximum stress still occurred in the minor radius, and although the stress was reduced for each run having additional stiffeners, the factor contributing most to the stress changed from in-plane bending-produced to axial load-produced stress.

The last variation in the initial set of runs was to connect the major arc lobes of each coil together (an intra-coil connector), in addition to the minimum inter-coil connectors every 90°. These intra-coil connectors, placed in the plasma stay-out zone, reduced the case stress to 10% below what had been attained with inter-coil connectors every 3° of arc.

Since all of the computer runs in the first set of analyses had unacceptably high case stresses, the basic 4-in. case thickness was increased for the second set of runs. In addition to the stiffening cited above, we added an axially-continuous angle bracket between the two coil cases to both transfer and help carry loads. This configuration also had gussets to provide good coil-to-coil stiffness and is shown in Figure 2-1. By firmly fastening the angle bracket to each coil case to permit efficient load transfer, the case stresses were reduced to more acceptable levels.

Fig. 2-1 Preliminary Design With 15-Degree Spaced Intercoil Stiffeners

The third set of runs was used to study local reinforcement of the minor arc region to increase its bending strength. A structure such as that shown in Figure 2-2 accomplishes two things. First, it increases bending strength for in-plane loads in the minor arc. Second, its box-like extension takes loads directly from the major

arc of the adjacent coil and transfers them to the reinforced coil where they are carried as in-plane bending in the major arc. The eccentric load path of an angle-shaped inter-coil structure is avoided so that torsion in the case is reduced. Using the stiffness of the 8.25-inch thick angle of Figure 2-1 as a base, a series of runs examined the effect of making such minor radius reinforcement ten times as stiff over various fractions of the arc. A factor of three times the angle stiffness is a practical limit using a box beam section with 8.25-inch uniformly thick walls.

Fig. 2-2 Small Radius Reinforcement Design

A similar structural analysis was performed for a Yin-Yang coil to be used in the end plug of a Tandem Mirror Power Reactor design by a team for the University of Wisconsin (Ref. 5). This design consisted of a low-strength Yin-Yang nested within

a pair of high-strength Helmholtz solenoidal coils. This combination produced a maximum 14.5 Tesla field strength at the conductor. The analysis demonstrated that the electromagnetic loads on the Yin-Yang could be carried by a uniform 20-cm thick coil case stressed to an allowable 80 ksi. A comparison of the coil case properties appears as Table 2-1. A comparison of the running loads acting on the conductors appears as Figure 2-3. Although the loads on the Wisconsin coil are considerably higher than those on the TMR Yin-Yang, a direct scaling of case thicknesses does not apply. The presence of the Helmholtz pair in the Wisconsin design prevents the plasma fan from spreading as rapidly as it does in the present TMR design. Therefore, it is possible to use direct intra-coil coupling for the Wisconsin design which will be shown to be a tremendous advantage not available to the present TMR design.

TABLE 2-1 COMPARISON OF COIL CASE PROPERTIES

	Wisconsin	Initial Design LLL #1	Final Design LLL #2
Case Wall Thickness	= 7.87 in.	4 in.	4 3/4 in./6 in.
Effective Area	$1.29 \times A_{\text{case}}$ = 2222 in. ²	$1.5 \times A_{\text{case}}$ = 1290 in. ²	$1.0 \times A_{\text{case}}$ = 1290 in. ²
Major Moment of Inertia	1.33×10^6 in. ⁴	$.71 \times 10^6$ in. ⁴	1.242×10^5 in. ⁴
Minor Moment of Inertia	4.23×10^5 in. ⁴	$.627 \times 10^5$ in. ⁴	1.8×10^5 in. ⁴
Major Section Modulus	32,200 in. ³	15,662 in. ³	25,725 in. ³
Minor Section Modulus	19,900 in. ³	5,660 in. ³	12,830 in. ³

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Most of our calculations applied conductor body forces directly to the case. That is, the conductor was assumed to act integrally with the case even though no allowance was made for the conductor banding stiffness. Except in the initial 4-inch thick case runs, the conductor was assumed to carry no load. However, by designing a gap between the conductor and case, the conductor may be allowed to deflect radially in the minor arc without contacting the case. The outward radial forces in the minor arc then cause hoop tension in the conductor which can be reacted as inward radial loads

Fig. 2-3 Force per Unit Length: Wisconsin vs. LLNL

on the less highly stressed major arc case. As will be seen, this creates a less severe peak stress at the smaller arc and thus provides a more favorable baseline design. Such transfer of load by the conductor is, in fact, unavoidable. Mechanical behavior tests of conductor packs have demonstrated an early reduced compressive stiffness due to an average 0.005-inch gap per winding layer.

The final design for the coil support structure uses the continuous angle beam fastened to both coil cases and stiffened with discrete gussets. The model case thickness varies from 4-3/4 in. to nearly 6 in. The angle stiffener is a constant 8-1/4 in. thick. As shown in Figure 2-4, the design uses a winding jacket inside a structural case, similar to the concept used on MFTF. Structural properties of the case used in the model assume that the stainless steel jacket and primary case combine to

Fig. 2-4 Coil Case Properties - Detailed

act together when loaded. The combination of this strengthened coil case, a design that includes the effect of conductor/case gaps at the small arcs (as described in the previous paragraph), and the use of increased stiffness for the inter-coil structure in the minor arc region, i.e., a box structure that is three times as stiff as the original angle, reduced peak stress in the minor arc to 95 ksi. This combination of arc, stiffeners, and load redistribution, represents our final proposed design.

3 - STRUCTURAL MODEL

3.1 COIL ELEMENTS

Because of the preliminary nature of the present design study, the modeling philosophy involved creation of a simplified structural idealization and analysis procedure which would facilitate exploration, while supplying results that would guide the design process. Of major concern were the peak internal stresses and configuration options available for supporting the primary electromagnetic loads. The goal was to develop an idealization that would be simple to construct and modify, that would yield results which were easy to interpret, and that could highlight the consequences of major design decisions regarding the primary structure. A beam model, together with a standard finite element program, was thought to embody all these features, and so was selected to achieve these objectives.

Each coil is composed of two large and two small semi-circular, planar, connected arcs as was shown in Figure 1-1. The smaller arcs are parallel to one another and are perpendicular to the larger arcs. Projections of the TMR Yin-Yang end-plug magnet centerlines are shown in Figure 3-1. Because of the geometrical and loading symmetry, it was not necessary to model the entire coil. For analysis purposes, the 1/4-symmetric model shown in Figure 3-2 was selected. A total of 30 smaller equal-lengthed straight beam elements and 30 longer equal-lengthed beam elements were used to construct two planar circular arcs for each coil. Figure 3-3 indicates the node numbering sequence for the two 1/4-coil models.

3.2 SUPPORT ELEMENTS

Besides modeling the coils and their cases, the system support structure required special treatment. Three distinct types of structural support systems were considered, as well as various combinations of these. The first type of support system which was investigated is referred to as "intercoil" stiffening and refers to the connections between the two coils. The intercoil connections are depicted generically in Figure 3-3. A second type of support system involves the use of stiffeners to connect one part of a coil to itself. These are termed "intracoil" stiffeners and are depicted in Figure 3-4. The third generic type of stiffener is associated

Fig. 3-1 Yin-Yang Coil Centerlines

with a curved beam that is similar in shape to the Yin and Yang coils and is contained midway between them (see Figure 3-5). Its purpose is to act as a curved beam support for each coil. This type of stiffener obviously requires some type of connection to the coils as well, but this attachment is not shown in Figure 3-5. As mentioned earlier, each of these type stiffeners, as well as various combinations of them, were considered in the trade studies to be described.

Since the main point of this study was to establish design feasibility and efficacy of the different support systems, simple beam elements were again used to represent the stiffeners.

Fig. 3-2 One-Quarter Stick Models of Each TMR Coil

3.3 ELEMENT PROPERTIES

Two types of cross sections were considered for the coils and their cases. The first was a conductor surrounded by a uniformly thick case (see Figure 3-6), while the second was a conductor surrounded by a more detailed nonuniform case (see Figure 3-7). The conductor bending stiffness was ignored in both cases; their stretching stiffnesses were included in the uniformly thick case, but not in the non-uniform case. The relative orientation of both coil cross sections is depicted in Figure 3-2.

Fig. 3-3 Discrete Intercoil Stiffeners

The stiffener properties were varied from case to case to determine the range of parameters required to minimize stresses in the conductor. Once the desired support stiffnesses were established, the feasibility of achieving such properties in a more realistic design was assessed. If it was felt that the required stiffnesses were achievable, this aspect of the design was incorporated. However, if a certain stiffness was not possible, alternatives were sought. The basic angle properties used are depicted in Figure 3-8 and multiples of these properties were selected in the parametric studies performed. The additional basic stainless steel coil case properties used were as listed in Table 3-1.

TABLE 3-1 STAINLESS STEEL CASE PROPERTIES

Temperature	-425°F
Modulus of Elasticity	$E = 29.6 \times 10^6$ psi
Poisson's Ratio	$\gamma = .271$
Yield Stress	$\sigma_y = 120$ ksi
Tensile Strength	$\sigma_u = 250$ to 300 ksi
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Fig. 3-4 Discrete Intracoil Stiffeners

Fig. 3-5 Curved Beam Stiffener

Fig. 3-6 Original Coil Case

Fig. 3-7 Coil Case Properties - Detailed

3.4 BOUNDARY CONDITIONS

As noted earlier, because of the symmetry of the coil, support geometry, and electromagnetic loading, it was only necessary to model one-fourth of the Yin-Yang coil pair. Thus, appropriate symmetry conditions had to be imposed at the model's boundaries to effect the desired internal load and deflection response symmetry. Accordingly, the y deflections and x and z beam rotations were set to zero at Nodes 1 and 101 (see Figure 3-2). Similarly, the z deflections and x and y rotations were set to zero at Nodes 61 and 161. This set of symmetry conditions still permitted a rigid body translation in the x direction, and so it was necessary to restrict this motion, at some arbitrary structural node point, to avoid a singular

Fig. 3-8 Finite Element Model of Coils With Angle Connecting Beam

stiffness matrix. After selecting the zero x-deflection stabilization node, it was possible to average the resulting x-deflections at Nodes 101 and 61, to subtract this value from the x deflection at Node 101, and to impose this new value as the x-deflection at Node 101 in a subsequent run. In this manner, it was possible to obtain a universal symmetry for all of the deflection components.

3.5 ELECTROMAGNETIC LOADS

The electromagnetic loads data on the Yin-Yang coil centerline were developed at the Lawrence Livermore National Laboratory. The numerical results were obtained using the EFFI code (Ref. 6). The applied loads are plotted in Figure 3-9 as inplane and out-of-plane running load components on the semi-major and semi-minor arcs. The center of each arc is denoted on either end of Figure 3-9. The inplane load components are directed radially outward and are largest on the smaller arcs. The out-of-plane loads on each coil act to open each coil at both the smaller and larger arcs, but the effect is more pronounced at the smaller arcs since the load components are much larger along the larger semi-circles. The running load component projections are drawn, approximately to scale, on the coil arcs in Figure 3-10.

Fig. 3-9 EM Loads on Coil Arcs

Fig. 3-10 EM Loads on Yin Coil

In preparing input for the structural model, it was necessary to multiply the local running load components by the length of coil arc associated with each node, to decompose the inplane loads into Cartesian coordinates and to apply them at the structural model nodes. Application of the load in this manner, directly to the coil cases, assumes that the conductors fit snugly within their structural cases and so pass their local body loadings directly to them. However, as introduced in Section 2, an important exception to this was considered whereby the small arcs' inplane radial loads were assumed to be carried entirely by the conductors themselves, rather than their cases. This condition was investigated in an effort to reduce case stresses at the small arc centers. This situation could be physically realized if there were sufficient clearance between the outside of the conductor bundle and the inner wall of the case of the small radius arcs, so that the case would not contact the coil as the small arc of the conductor bundle developed hoop stress and expanded radially. These outward forces could be reacted eventually by inplane radial loads on the large case arcs. For simplicity, it was assumed that the large arc reaction loads were uniformly distributed resulting in the net case loads depicted in Figure 3-11. The associated strain in the conductor had to be checked for such cases to insure that the hoop component was not excessive for the load condition designed for.

Fig. 3-11 EM Loads on Yin Coil Case

4 - ANALYSIS RESULTS

4.1 NUMERICAL RESULTS

A series of numerical studies were performed on the IBM 370/168 computer using the cosmic version of the NASTRAN structural analysis computer code (Ref. 7), and the models described earlier in Section 3. From a perusal of computer run output, it was rapidly determined that the critically stressed coil section was located at the center of the smaller arcs, and that the peak stresses were caused by a combination of direct and bending loads.

The initial structural model data submittals involved a series of trial cases in which the coil supports involved either discrete intercoil stiffening only (see Figure 3-3) or intracoil stiffening (see Figure 3-4). The stiffnesses of the connecting members were varied, being made both large and small compared to the case properties, to ascertain the effect of stiffness upon case stresses.

The first set of results generated for the 4-inch uniform wall thickness case of Figure 3-6 revealed that the preferred design approach for supporting the electromagnetic loads was through the use of intracoil stiffening (see Cases 3 and 4 of Table 4-1). As may be seen, this type of support tends to reduce peak stress levels by a factor of 3. Unfortunately, the use of direct intracoil stiffeners, as depicted in Figure 3-4, interferes with the shape of the plasma which fans out between the large circular arcs. Therefore, further studies using intracoil stiffening were not considered.

The other observation that is evident from the results of Table 4-1 is that intercoil supports (as depicted in Figure 3-3) become more effective as they are made stiffer. As only two intercoil stiffeners were used for cases 1 and 2 of Table 4-1, additional stiffeners were employed. The results of using intercoil stiffeners every 15, 9, 6 and 3 degrees of arc are presented in Table 4-2. As may be seen, these results indicate an improvement in peak stress with increased intercoil stiffness. A typical design showing such stiffeners is presented in Figure 4-1.

Also included in Table 4-2 are the results from employing a continuous angle connector (see Figures 3-5 and 3-8). Once again, this type of stiffening is seen

TABLE 4-1 TMR YIN-YANG COIL CASE STRESSES FOR A UNIFORM 4 INCH WALL THICKNESS CASE

Case No.	Description	Stress (ksi) at Center of Large Radius				Stress (ksi) at Center of Small Radius			
		P/A	Bending	Components	Peak	P/A	Bending	Components	Peak
1	Four flexible connections at arc centers between coils	20	66	28	115	47	537	31	615
2	Two stiff connections at arc centers between coils	24	115	75	213	24	447	54	524
3	Same as Case 1 + 2 stiff intra-coil supports at the center of the major arcs assisting the small radii	20	66	51	137	31	88	45	163
4	Same as Case 2 + 2 stiff intra-coil supports at the center of the major arcs assisting the small radii	19	51	44	114	31	87	44	162

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Case No.	Description	Stress (ksi) At Center of Large Radius				Stress (ksi) At Center of Small Radius			
		P/A	Bending	Components	Peak	P/A	Bending	Components	Peak
1	Soft Inter: Four soft connections at arc centers between coils	20	66	28	115	47	537	31	615
2	Stiff Inter: Four stiff connections at arc centers between coils	24	115	75	213	24	447	54	524
5	Stiff 2: Stiff connections every 15° of arc between coils	9	82	11	102	77	97	31	205
6	Stiff 3: Stiff connections every 6° to 9° of arc between coils	15	60	5	80	83	72	45	200
7	Soft 2: Soft connections every 15° of arc between coils (100 times softer than for "stiff 2")	32	211	11	254	36	290	45	371
8	Stiff 5: Stiff connections every 3° of arc between coils	20	43	1	64	88	49	44	181
9	Angle 1: Continuous angle connection between coils	25	91	1	118	38	140	34	212
10	Angle 2: Same as "Angle 1" except that angle stiffness properties are double	22	56	1	79	38	97	29	165
11	Angle 4: Same as "Angle 1" except that angle stiffness properties are a factor of 10 higher	12	8	4	24	35	26	19	79

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to reduce coil case stresses significantly and the improvement is strongly dependent upon the stiffness of the support angle employed.

Fig. 4-1 Preliminary Design With 15-Degree Spaced Intercoil Stiffeners

Table 4-3 shows the intercoil and angle stiffening connection effects upon the nonuniform case design (see Figure 3-7). The various regions over which the angle is stiff (see cases 13 through 14 of Table 4-3) are depicted generically in Figure 4-2.

Up to this point, only the results for the loading of Figure 3-10 have been presented. Table 4-4 indicates the effect of employing coil case clearance at the outer radius of the small arc, resulting in the coil case loading of Figure 3-11. These results, when compared with those for the load case of Figure 3-10 (no coil/case clearance), indicate that the clearance design feature is an effective manner for reducing peak case stresses. The results, for a factor of 3 stiffening angle property-multiplier, were generated because it was felt that this was a more realistic design possibility, whereas a factor of 10 property-multiplier was less

TABLE 4-3 INTERCOIL AND ANGLE CONNECTION EFFECTS UPON TMR YIN-YANG PEAK STRESS FOR NEW COIL CASE DESIGN

Case No.	Description	Stress (ksi)			
		At Center of Small Radius			Peak
		P/A	Bending	Components	
5	Stiff connections every 15° of arc between coils	67	84	4	155
9	Continuous angle connection between coils	40	109	20	168
12	Very stiff angle connection (10 x Case 9 stiffness) continuous	33	32	18	83
13	Similar to Case 12 but angle is stiff only over 60% of coil	33	59	13	105
14	Similar to Case 13 but only for 53% coil	33	65	13	111
15	Similar to Case 13 but only for 47%	34	70	14	119
16	40%-otherwise similar to 13	35	77	15	126
17	33%-otherwise similar to 13	35	83	16	134
18	27%-otherwise similar to 13	36	89	16	142
19	20%-otherwise similar to 13	37	95	17	149

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Fig. 4-2 Small Radius Reinforcement Design

realistic. It is interesting to note that the use of a stiff angle over only 40 percent of the coil, with the loads of Figure 3-11, is almost as effective as if this angle existed over the entire coil (see cases 16.1 and 16.2 of Table 4-4).

4.2 DISCUSSION OF NUMERICAL RESULTS

In comparing the preliminary structural requirements of the TMR Yin-Yang coils with results of the present conceptual design and analysis study, it appears that the concept proposed at the end of Section 2 and listed as Case 16.1 of Table 4-4 is only marginally acceptable. It has been customary, in similar studies, to select a peak nominal stress of two-thirds the yield stress as a design criterion. As may be seen from the present feasibility studies, the structure depicted conceptually in Figure 4-2 yields a peak stress of 95 ksi. This stress is somewhat higher than two-thirds the yield stress (of 120 ksi) for the stainless steel material contemplated in Section 3.3.

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TABLE 4-4 PEAK STRESSES IN COIL CASE WITH AND WITHOUT CASE/CONDUCTOR CLEARANCES

Case No.	Description	Peak Stress Components (ksi) at Center of Small Radius			
		P/A	Bending Components		Sum
			Inplane	Out-of-Plane	
9	Original loads (Fig. 3-10) Original angle properties	39	109	20	168
12	Original loads (Fig. 3-10) 10 x original angle properties	33	52	18	83
16	Original loads (Fig. 3-10) 10 x angle properties for 40% of coil	35	77	15	126
9.1	New loads (Fig. 3-11) Angle connected Original angle softly to cases	13	113	21	147
9.2	Angle connected stiffly to cases	25	83	13	121
16.1	New loads (Fig. 3-11) 3 x original angle properties over 40% of coil	20	64	11	95
16.2	New loads (Fig. 3-11) 3 x original angle properties over 100% of coil	20	59	10	89

* Coil case referred to in this table is shown in Figure 3-7.

** With case/conductor clearance refers to loads of Figure 3-11.

*** Without case/conductor clearance refers to loads of Figure 3-10.

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Note, however, that a number of considerations must be investigated before accepting or rejecting the present concept on purely structural grounds. For example, the ultimate stress for the contemplated case material is between 250 and 300 ksi, which is more than twice the yield stress. This fact might permit relaxation of the two-thirds yield peak stress limitation to a somewhat higher ratio. Furthermore, more detailed stress analysis might reveal a higher or lower nominal stress in the critical region of the coil case, depending on local detail effects. For example, it is believed that thick-beam stress effects, which definitely occur on the circular arcs, would raise the peak stresses above the present values which were computed using thin beam theory.

5 - CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate the distinct advantage of intracoil connectors across the lobes of the major arc and this fact was made use of in the Wisconsin reactor design study of Ref. 5. However, for the present TMR, the reactor plasma fanshape occupies the space between the major arcs and so no structure can be placed there. This was not the case in the Wisconsin high-field (14.5T) Yin-Yang coil reactor study in which Helmholtz barrier coils reduced the fan spread-width considerably, and intracoil stiffening was possible.

Most of the calculations performed in this study applied the conductor body forces directly to the case. However, some examples in which the conductor was allowed to deflect radially along the minor arc, without making contact with the case, were run. The small arc radial forces were then transferred to the case as inward radial loads on the major arc, which was a less highly stressed region. These analyses resulted in lower maximum case stresses. More detailed analyses, using a more refined structural model, could pinpoint an optimum configuration and further improve the design.

Our marginally acceptable final design, for the coil support structure is shown in Figures 3-7 and 4-2 with loads shown in Figure 3-11 and stresses listed as Case 16.1 of Table 4-4. We used the continuous angle beam fastened to both coil cases, and stiffening with discrete gussets. In the vicinity of the small radius, the angle was built into a box section. This box section was three times as stiff as the angle alone and extended for approximately 40 percent of the coil path. The proposed final design used design clearances in the minor arc to transfer loads via the conductor to the less highly stressed major arc.

It may be seen from this work that it should be possible to design an acceptable structural support system for a Yin-Yang end plug in a tandem mirror reactor with thermal barriers. It is recommended that more detailed design and analyses be conducted to pinpoint an optimum loading configuration and refine the overall case design.

6 - REFERENCES

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