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DESIGN AND ANALYSIS OF THE INTOR TOROIDAL FIELD-COIL STRUCTURAL SYSTEM*

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Summary

The International Tokamak Reactor (INTOR) is a unique collaborative effort among the USA, USSR, EURATOM, and Japan to define the characteristics and objectives of, assess the technical feasibility of, and develop a design for the next major experiment in the world-wide tokamak program. The conceptual design consists of twelve toroidal field (TF) coils, each having a bore of 7.75 X 10.7 meters and a maximum field of 10.8 Tesla. The all-external poloidal field (PF) coil system imposes a very large pulsed field on the TF coil system. The superconducting TF and PF coils are enclosed by a common vacuum cryostat which includes individual enclosures for each TF coil's outer leg. This configuration provides a large "window" through which a complete torus sector can be withdrawn. The purpose of this study was to develop a feasible TF coil structural system design. The various design criteria and their effects on the design are discussed. The rationale supporting the allowable cyclic stress of 200 MPa (29 ksi) is discussed. Support of the TF coil outer legs for the large pulsed out-of-plane loading while maintaining the "window" area and considering the relatively low allowable cyclic stress presented a most difficult design problem. Details of the mechanical design and assembly method are presented. The feasibility of the structural design was investigated using a three-dimensional NASTRAN finite element model (FEM) and by suitable local analyses of critical areas. The FEM consisted of 637 elements and 614 grid points having a total of 5197 degrees-of-freedom for each of the 24 half-segments modeled. Variations of the basic FEM were used to investigate structural load paths of interest. Details of the FEM used and the significant results of the structural analyses are presented. A discussion of the generic advantages and disadvantages of several structural load paths of interest is included.

Design Criteria and Effects

The TF coil support structure must effectively support the magnetic, gravity, seismic, and fault load conditions that will be encountered during the life of the reactor. The TF coil and its support structure is an integral part of the reactor, providing support for the PF coils and access to the torus. Therefore, the TF structural design must follow a systems design approach which allows it not only to meet its own requirements but also the requirements of the total device.

It is important to define a structural load path to support the out-of-plane magnetic loads acting on the TF coil in a manner that is compatible with the torus design and maintenance approach.

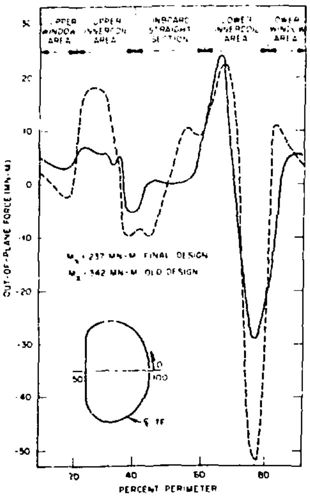
To retain a TF window with sufficient access to accommodate 12 torus sectors requires incorporating either a thick wall TF coil design or a built-up structure arrangement. A thick wall TF case design provides for additional bending stiffness by increasing the coil cross section along the outside of the coil. This approach runs into difficulties in terms of eddy current heating in the thick plates associated with the PF coil field changes plus problems in fabrication and void detection. The structural arrangement selected substantially reduces these problems by incorporating a built-up structure using relatively thin plates with stiffeners.

The magnetic system structural design criteria include conventional stress limits in addition to limits established for peak stress based on crack growth and fracture mechanics considerations. The limit on peak normal stress is dependent upon the number of design pulses and upon the stress ratio f, defined as the ratio of the amplitude of cyclic stress divided by the total stress. In addition, the design allowable is influenced by material properties (fracture toughness, crack growth constants), desired safety factors on stress and cycles, and upon the minimum size flaw which can be guaranteed to be detected during inspection.

During the Phase I Workshop, the engineering group discussed the existing technical level of flaw detection ability, the impact of fracture mechanics evaluations , considering the ideas of an initial flaw threshold value and the problem of using fracture mechanics principles in the cryogenics area because of a lack of material data. The outcome of these discussions was to agree that until more research and development work is available for large magnet systems operating at cryogenic temperatures, smooth specimen fatigue data should be used for preliminary design purposes. With the limited data available on stainless steel, an allowable stress of 200 MPa (29000 psi) was suggested using factors of safety of 3 on stress and 20 on number of cycles. The INTOR team concurred with this criterion and adopted it as the stress allowable.

Magnetic Loads

The magnetic forces acting on the TF coil result from self forces of the TF winding plus the interaction of the TF current and the PF coil magnetic field. Each of the 12 toroidal field coils (7.7-m X 10.7-m bore dimensions) has an 11 T peak field at the TF winding. The final PF coil locations and currents produce an overturning moment of 237 MN-M on each TF coil and an out-of-plane force distribution as shown below. Note the locally high loading in the lower outer intercoil region.



TF COIL OUT-OF-PLANE LOAD

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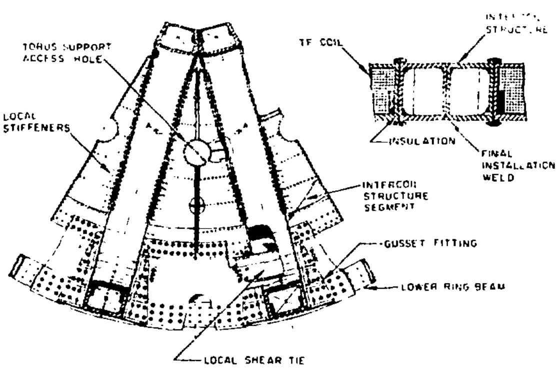
Structural Arrangement Design Description

The TF coil itself consists of 5 cm cover plates, outer TF coil ring and stiffeners, plus a 10 cm inner bobbin. The required spacing and thickness of the in-plane stiffeners in a final TF coil case design will be determined after the load carrying capability of the coil winding is defined. The TF coil is completely isolated electrically from the intercoil structure by electrical insulation which reduces the eddy currents in the TF coil case. The section view of the intercoil support structure shows the gusset fittings (5 cm thick) bolted to the outer TF coil leg, an outer ring beam and a 5 cm-thick intercoil structure which provides the moment support for the gusset fitting. The thickness and stiffener spacing in the gusset fitting and intercoil structure are sized to support the additional out-of-plane pressure not supported by the 5 cm side wall thickness of the TF coil case. A fiberglass isolation sheet is located on each side of the TF coil to reduce the toroidal eddy current path. A flange interface is provided along the TF and intercoil upper and lower surfaces to simplify a bolted connection between the two structures. During preassembly fitup of the TF coil case and intercoil structure, an epoxy layer will be applied between the two surfaces to assure a tight fit. A structural weld is located at the mid-span between TF coils to simplify final installation. The intercoil and outer ring structure act integrally to support the TF coil forces. To improve the torsional stiffness of the inner TF coil region, an intercoil shear tie between TF coils plus a shear connection to the bucking cylinder was incorporated.



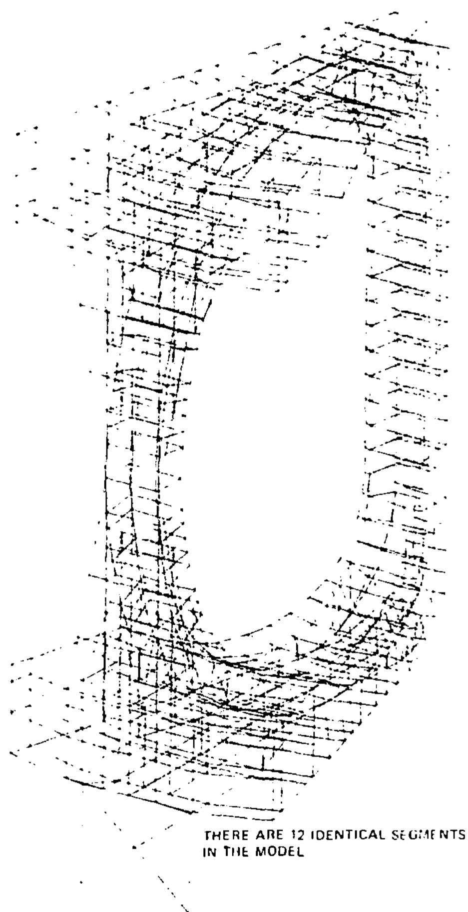
PLAN VIEW OF TF INTERCOIL STRUCTURE

TF Coil Support System Structural Analysis

The structural analysis was performed on an earlier configuration which located the lower outside PF coil near the TF winding. Since the final PF configuration relaxed the local magnetic loading condition on the TF coil and provided more space for the lower outer ring beam, a new structural model was not generated. All deflection and stress data presented is for the more severe loading associated with the earlier configuration.

Two levels of structural analysis were used. The first was a computer model using the finite element technique to establish global distributions of internal load and stress. The second level of analysis was local analysis to study the details of the design.

Finite Element Analysis. The finite element model, of which there were six major iterations to investigate various effects, is based on the NASTRAN code. The analysis method used cyclic dihedral symmetry for which the NASTRAN code formulates the boundary conditions. The method used results in a significant reduction of computational effort beyond the normal possibilities of substructure analysis. The applied loads are not required to possess symmetry, and geometry is input for only the half sector. The TF coil structure was modeled using plate elements. The effect of the conductor winding was accounted for by first determining equivalent plate thickness necessary to produce acceptable stress levels followed by determining how much of this equivalent thickness was really case thickness and how much was equivalent to the coil pack axial area. The out-of-plane bending stiffness of the coil pack was assumed negligible with respect to that of the intercoil structure.



MKIIIA - NASTRAN FINITE ELEMENT MODEL

A discussion of the more significant stress magnitudes for each of the major structural components will be addressed in the following paragraphs.

Bucking Cylinder. The bucking cylinder supports approximately 30% of the total centering force on each TF coil. The intercoil structure serves as a large wedging structure to carry a major portion of the centering load. The average principal stress in the bucking cylinder is 400 MPa due to the steady loading of the TF coils. With the addition of the torsional tie to the intercoil structure, an additional stress of

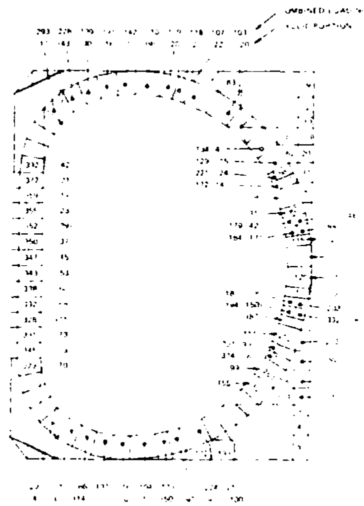
43 MPa due to the cyclic out-of-plane loading was obtained. These stress levels are within the allowable range. Locally higher stresses can be expected in the region of the bucking cylinder dielectric breaks. The largest stress is in the circumferential direction. Since it is a compression stress throughout the thickness of the cylinder, large stress risers are not expected. Dielectric joints in the axial direction (i.e., cuts in a horizontal plane) could be designed using a vertical tab and slot arrangement similar to that used on TFTR. The bucking cylinder does not appear to be a problem when a thickness of 0.27-m is used.

Intercoil Shear Tie. The intercoil shear tie represents an actual (perhaps bolted in place) shear connection between the TF coil inboard legs. It serves to stiffen the inner structure torsionally and also provides a wedging action of the TF coil noses. Investigation shows that it carried 9% of the centering force by the inner bobbin of the TF coil case (i.e., that portion of the bobbin located in the nose region). It would be expected that this hoop load would not be carried across the winding cavity itself due to the relatively flexible load path through the conductor pack. It should be pointed out that wedging action is required for the TF coil side walls to be mutually supportive in the presence of the plate bending induced by the TF conductor pack out-of-plane loads. Also, it is required to insulate the bolts and plate used to provide a shear tie if this option proved desirable. Stress levels in the shear tie are at an acceptable level with a TF coil in-plane load-induced stress of 218 MPa. The cyclic stress which would be added to this if a shear tie option were adopted is 40 MPa.

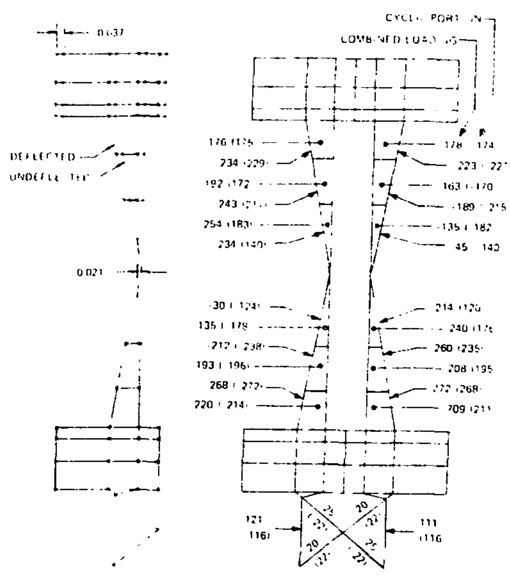
TF Coil Side Plate. The TF coil case side plate total stress in the nose region (as in the TF [illegible] in general) should be divided into in-plane and out-of-plane components induced by the TF coil loads. In a typical example, this yields 350 MPa in-plane and 42 MPa out-of-plane. The in-plane component should then be reduced by apportioning to the conductor pack effective axial area a part of the axial (in-plane) stress (load). It was determined that approximately 50% of the axial load in the case would be carried by the conductor, resulting in a case stress of 175 MPa. To this is added the out-of-plane stress (175 + 42), giving a total average stress of 217 MPa. This is admittedly a crude approximation; however, it does give an indication that the global stress level in this area is reasonable. The conductor maximum strain is approximately 0.0075%. This corresponds to a stress of approximately 200 MPa in the copper stabilizer. These stress values are due almost entirely to in-plane steady loading. In summary, stress levels in the TF coil case were found to be acceptable. Careful attention must be paid to the relatively highly stressed lower outer portion of the TF coil. In an opposite sense, the upper outer portion is lightly stressed, and a reduction of structural thickness should be considered.

Intercoil Stiffeners The intercoil stiffeners of the gusset fitting are major structural members designed to stiffen the window area of the TF coil case against out-of-plane TF coil loads. Average principal stress in these plate elements was above the allowable level, due almost entirely to out-of-plane cyclic loading. The addition of a flange to the two outer stiffeners of the gusset fitting was found to be the most effective approach. Detailed design is required to determine if it would be more desirable to provide additional stiffeners, each of smaller cross section than those currently modeled. However for the modeled-cross sectional area of 0.06-m^2, the maximum tensile cyclic stress is 268 MPa. To reduce this to the allowable stress of 200 MPa, an area of 0.08-m^2 would be required. This area, while not optimized, would be reasonable and acceptable. It was also shown that the addition of stiffener caps proved to be the most effective means of reducing lateral TF coil deflections.

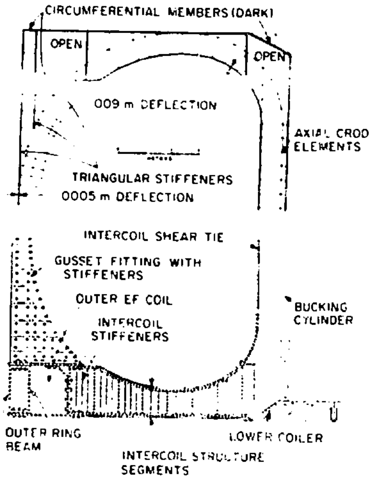
Collar. The stress level in the collar structure itself is acceptable. Stress due to in-plane TF coil loading is 138 MPa and the cyclic portion is 76 MPa. The purpose of providing this load path was to decrease stress in the balance of the structure. It was found that the stress in the intercoil stiffeners, as well as the structure in general, was decreased by approximately 10 . The maximum out-of-plane displacement of the TF coil is located in the middle of the upper outer portion of the TF coil. The addition of the torque-tie



MKIIIA- PRINCIPLE STRESSES (MPa)
TF COIL SIDE PLATE



MKIIIA - OUTER STIFFENER
DEFLECTION (m) PRINCIPAL STRESS (MPa)



COMPARISON OF FEM WITH STRUCTURAL LAYOUT

did not significantly decrease the maximum out-of-plane displacement. The primary benefit of using the torque-tie to the bucking cylinder is realized when considering the design details. It would be easier to provide suitable dielectric joints in the collar structure than to insulate the intercoil shear attachment bolts and provide a dielectric joint. A decision on whether to keep the intercoil shear tie structure must be made after further design.

Support of PF Coil Applied Loads. The radial load of the very large lower outer PF coil of the earlier configuration was applied to the model. The loading applied was of a magnitude equal to half that on the PF coil, assuming that the other half is supported by the PF coil itself. The largest radial deflection of the outer ring beam with the PF coil loading applied is 0.0048-m which is considered small. The highest stress in the intercoil structure is 295 MPa of which 106 MPa is cyclic due to the PF coil and 149 MPa is cyclic due to the TF coil out-of-plane loads. This locally high stress was expected due to the stress concentration of the "cutout" in the cover where the TF coil conductor passes through it. The total cyclic stress can be decreased by increasing the lower intercoil structure top cover plate thickness to 0.12-m in the local area around the "cutout" in the cover. A local stress of 221 MPa was calculated in the web. This high value was due to the assumed loading which was applied as a series of local concentrated loads. Refinement of the model to distribute the loading would decrease this stress to a low value. The highest stress in the remaining intercoil structure was 106 MPa which is acceptable.

It should be pointed out that this approximation of the PF coil loading does not include the benefit of the inherent axial and bending capability of the PF coil. Future, more detailed modeling of the whole PF coil structural system would be expected to show reduced stress levels and a very significant reduction in the stress level in the PF coils. It is concluded that the intercoil structure can greatly reduce the burden placed on a self-supporting PF coil structural system.

Local Stress Analysis

Three areas of interest were looked at with respect to support of local magnetic loads.

The TF coil case outer ring at the upper inner corner is heavily loaded by TF coil conductor in-plane radial pressure. Local stress analysis shows that a number of stiffening ribs will be required to assure that the combined global and local stress does not exceed the allowable. The allowable stress for this area is relatively high because the loading is steady-state and the cyclic global stress is not high.

The TF coil case side plate in the nose region is heavily loaded by the TF coil conductor cyclic out-of-plane pressure. Local side plate bending stress is such that it is necessary to have the adjacent TF coils closely fitted. This allows the adjacent TF coil's side plate to carry a portion of the pressure loading. The two side plates, while not acting as one, can together support the pressure loading.

The TF coil case side plate in the area of highest cyclic out-of-plane pressure at the lower outer corner of the TF coil was analyzed. The area of greatest concern was just above the bottom of the window area. It was necessary to increase the thickness of the gusset fitting plate over the TF coil winding area to decrease TF coil side plate stress to an acceptable level. It was also necessary to add local stiffeners in the area covering the winding cavity. These stiffeners, the detailed design of which remains to be accomplished, are a part of the intercoil stiffener structure.

Conclusions

The analysis performed to date shows very encouraging results. Overall global stress levels for the nominal loading conditions investigated were comfortably acceptable. Deflections are also reasonable. Areas of relatively high cyclic stress were identified. It has been shown how, with further design, these stress levels can be lowered to acceptable values. Of primary importance is the reduction in TF coil out-of-plane loading which resulted by incorporation of the final PF coil configuration. It is expected that the magnitude of the stress and deflection data discussed above would be appreciably less with an updated analysis incorporating the final PF coil design. The final conclusion of the present analysis is that a design has now been established for which a complete analysis should show feasibility. This analysis using time dependent variation in fields and forces must be provided to develop the final structural design.