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ISX TOROIDAL FIELD COIL DESIGN AND ANALYSIS[†]

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SUMMARY

Structural design and analysis aspects of the toroidal field coils for the Impurities Study Experiment (ISX) tokamak will be discussed.

The overall mechanical design of ISX is predicated on the ability to remove the upper segment of the toroidal field coils to allow access to the toroidal vacuum vessel. The high current, 120 kA, capability of the new 74 MW power supply, coupled with the modest field requirement of ISX, allows the use of room temperature copper coils. Seventy-two turns, grouped into 18 coils, generate a magnet field of 18 kG at the major radius of 90 cm.

Finite element structural analysis codes have been utilized to determine the distribution of stresses and deflections around a typical turn. Initial material distribution on a coil was sized using the two-dimensional program FEATS. The resulting coil design was then coupled to the center bucking and out-of-plane restraint systems utilizing the NASTRAN code. The boundary conditions for the analytical models used in the two programs were then iterated, reaching satisfactory agreement as to stress contours and location for the joints.

~~In order to demonstrate the electrical integrity of the joint design, specimens were prepared and tested at full design current. Three 1- x 4-in. cross-section copper bars, fabricated as lap joints in each plane, and in a "fingered" arrangement, all demonstrated the ability to conduct 120 kA.~~

INTRODUCTION

The Impurities Study Experiment (ISX) is an iron core tokamak device which uses rectangular shaped toroidal field coils to generate an 18 kG toroidal field at the major plasma radius of 90 cm. These coils incorporate bolted, demountable joints which allow the top section of each coil to be removed to provide easy access to the vacuum chamber and plasma liner. As shown in Figure 1, the coils are constrained to each other through a central fiberglass bucking cylinder and two fiberglass torsion cylinders. The torsion cylinders also serve as the support for the ohmic heating and vertical field coils.

This paper describes the analytic procedure used to support the structural design of the ISX toroidal field coil system. This procedure consisted of three major steps. First, appropriate electromagnetic loading conditions were determined. These conditions included normal operating conditions in which all coils were energized at expected current levels and a fault condition in which one toroidal field coil was assumed to be electrically removed from the system.

During the second step, a sizing analysis was performed on a single toroidal field coil using a two dimensional finite element model of the coil. This analysis, which considered only normal operating condition loads, was performed using the FEATS finite element computer program. A three-dimensional finite element model for a symmetric quarter section of the toroidal field coil system with constraining cylinders was developed for the third step in the analysis. The analyses performed with this model considered both normal operating and fault condition loads and used the NASTRAN finite element computer program.

DESIGN CONSIDERATIONS

The structural design process was initiated with the identification of a number of design goals. Some of these design goals include the following:

(1) The toroidal field coils should be made from copper or copper alloy plate having sufficient structural strength to carry all induced loads.

(2) The toroidal field coil joints should be located such that the inner components of the machine can be removed vertically when the top section of each coil is removed.

(3) The maximum stress should be minimized at each toroidal field coil joint location.

(4) The net centering force on each toroidal field coil should be reacted by a central fiberglass bucking cylinder.

(5) The out-of-plane forces on each toroidal field coil should be reacted by two fiberglass torsion cylinders.

(6) The displacement of the toroidal field coils and the toroidal field coil system should be minimized to prevent contact with the other components in the ISX device.

As discussed later in this paper, each of these design goals was essentially met in the final ISX Toroidal Field Coil System design.

LOADING CONDITIONS

The first step in the design/analysis process was to determine the electro-magnetic loads on the toroidal field coils. As shown in Figure 2, these loads include both in-plane effects as induced by the assemblage of toroidal field coil currents and out-of-plane effects as induced by poloidal field currents and toroidal field coil fault conditions.

The MAGNET computer program, which assumes the filament theory for magnetic field/force computations, was used to calculate the desired loads. This program is designed to determine loads in the toroidal field coil system of a tokamak device as induced by both toroidal and poloidal currents. These loads are calculated at designated points or nodes along each toroidal field coil centerline assuming prescribed coil geometry and electrical characteristics and the generated field strength along the plasma axis.

The MAGNET program was initially used to determine the in-plane, normal operating condition loads on each toroidal field coil. These loads were applied to a two dimensional finite element model of a typical toroidal field coil during the second step of the design/analysis process.

The TORMAC computer program was developed to calculate the various electro-magnetic loads in a format compatible with input to the NASTRAN finite element computer program. Results obtained from this program, which uses the MAGNET program as a subroutine for field/force calculations, were used for each of the analyses performed under the third step of the design/analysis process.

Two-Dimensional Finite Element Analyses

The second step of the design/analysis process was to determine the desired geometrical shape for a typical toroidal field coil. To do this, an approximate shape was selected and in-plane stresses and deformations were determined using the FEATS finite element computer program. Seven hundred and twenty-six (726) quadrilateral elements (6 elements across the width and 121 elements around the coil) were used to model one-half of the coil. Following an evaluation of analysis results, the geometry was appropriately modified and the finite element analysis rerun. This procedure was repeated until a suitable geometry was obtained.

A significant feature of the FEATS program is its capability to generate stress contour plots such as is shown in Fig. 3. Using these plots it was quickly possible to locate regions on the coil having low bending moments and high localized stresses.

Results from each iteration of the two-dimensional finite element analysis were evaluated to insure that maximum stresses were below allowable values throughout the coil and that bending moments were a minimum at each joint location.

THREE-DIMENSIONAL FINITE ELEMENT ANALYSES

Once a reasonable coil geometry was determined using the FEATS program, a three-dimensional finite element model of the toroidal field coil system was developed for use in evaluating the effects of poloidal field loads and toroidal field fault loads. The model used for this third step of the design/analysis process is shown in Figure 4.

It should be noted that this model, which is constructed from beam and plate finite elements, represents only a symmetric quarter section of the toroidal field coil system. As shown by Pardue and Johnson,[1] the stresses and deformations in the complete structure can be determined with this model for any combination of asymmetric loads.

Two sets of analyses were performed with the three-dimensional model. The first set considered the normal operating load conditions including effects of both toroidal and poloidal currents. As discussed in the next section, the in-plane results from these analyses were compared with the previously generated two-dimensional analyses and the complete results were reviewed to ascertain the added effects of poloidal field loads. The second set of analyses considered a fault load condition in which one complete toroidal field coil was electrically removed from the system. Results from these analyses are also described in the next section.

Summary of Results and Conclusions

Significant stress analysis results obtained during the design/analysis process are described below. Included are a comparison between in-plane results on a typical toroidal field coil obtained with both the two-dimensional and three-dimensional solutions and additional results obtained from the three-dimensional solution which consider the effect of asymmetric and/or out-of-plane loads.

Figures 5 and 6 show a comparison between in-plane bending moment and maximum stress distributions in a toroidal field coil using results from both two-dimensional and three-dimensional analyses. As seen from these figures, the results are in very close agreement, especially at the critical joint locations. The relatively large region of low bending moment along the inner leg of the coil is a significant result. These low bending moments and corresponding low values of transverse shear result in almost pure tenson stresses across this joint thus maximizing the probability of this joint to resist applied loads. As seen in Fig. 6, the maximum absolute stress occurs at the outer corner and has a value of approximately 20,000 psi.

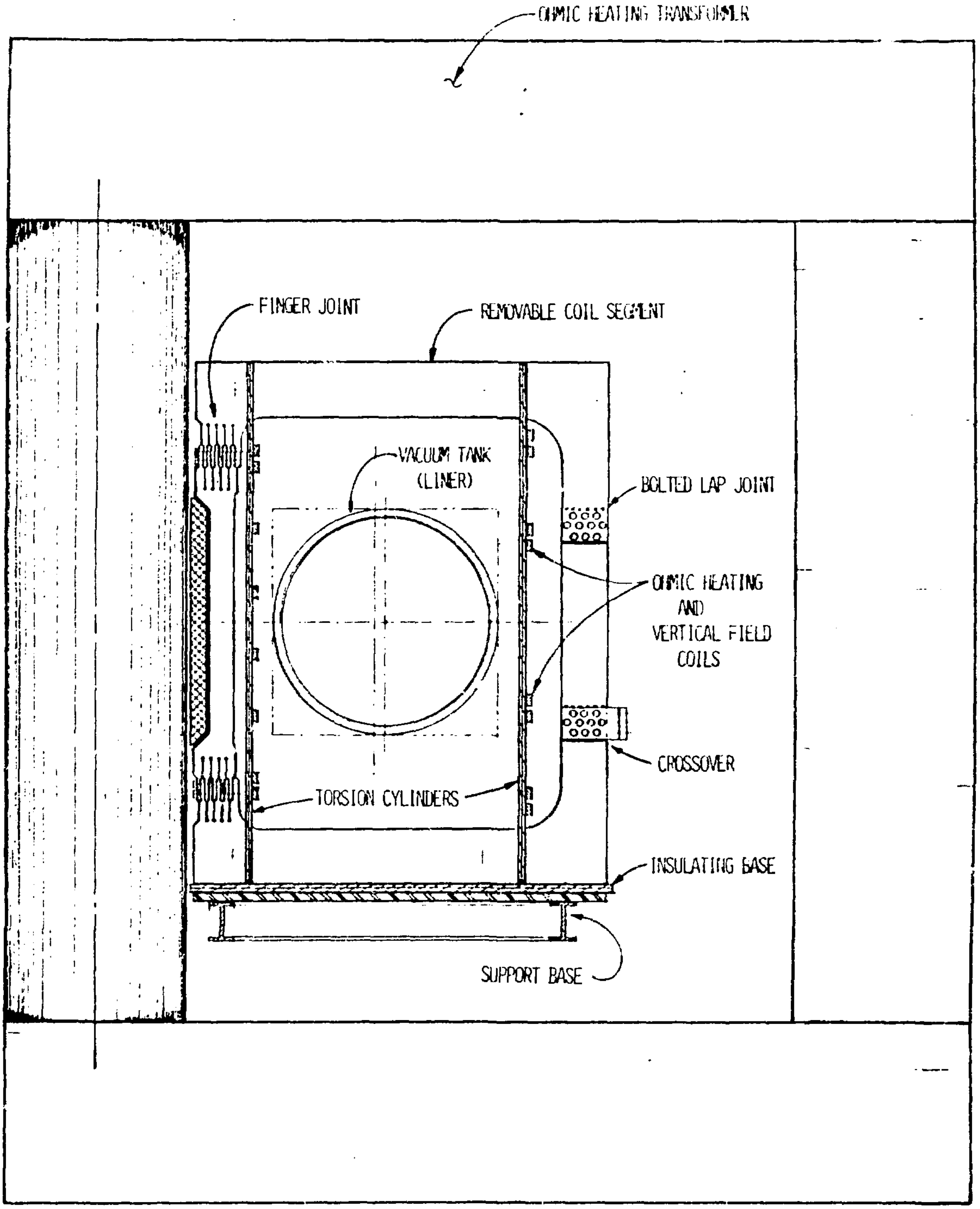
The resulting in-plane coil deflection can be seen in Fig. 8. Note that these deflections have been magnified for ease in determining the deflected direction. The maximum deflection occurs as a result of a fault condition and is approximately 1/10 of an inch at the outer corner.

Results from the three-dimensional analysis show the maximum stresses in the fiberglass torsion and bucking cylinders as well as the toroidal field coils occur as a result of a fault condition. These maximum stresses in the inner and outer torsion cylinders are -5,000 psi and + 6,000 psi respectively and occur at the intersection of the coil and the cylinder. The bucking cylinder sees a compressive stress of approximately 16,800 psi.

As seen in Fig. 2, the loads encountered on each coil as a result of a fault condition are away from the "zero current" coil. The resulting displacements of the coils for this fault condition can be seen in Fig. 9. As expected, the displacement of each coil is away from the the "zero current" coil. These deflections, as previously mentioned, have been magnified for ease in determining the deflected direction. All stress values and deflections encountered both for the normal and fault loading conditions were acceptable and did not offer any real insolvable problems in the design of the coil system.

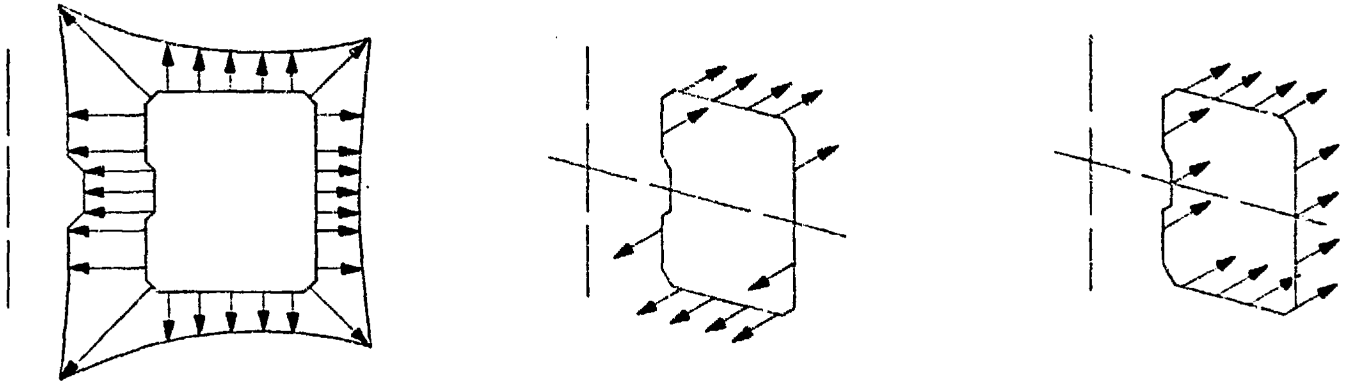
REFERENCES

1. Pardue, R. M. and Johnson, N. E., "A Structural Analysis of an Experimental Power Reactor Magnet System," paper presented at the Sixth Symposium on Engineering Problems of Fusion Research, San Diego, California, Nov. 18-21, 1975.



ISX CONCEPT

FIG 2

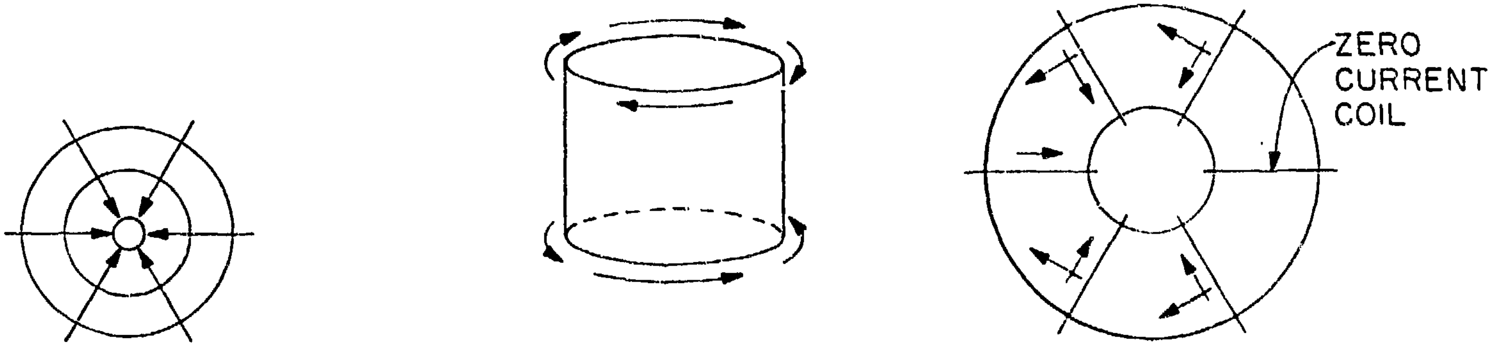


IN-PLANE LOADS FROM TOROIDAL FIELD COILS

OUT-OF-PLANE LOADS FROM POLOIDAL FIELD COILS

OUT-OF-PLANE LOADS FROM FAULT CONDITION

LOADS APPLIED TO EACH COIL



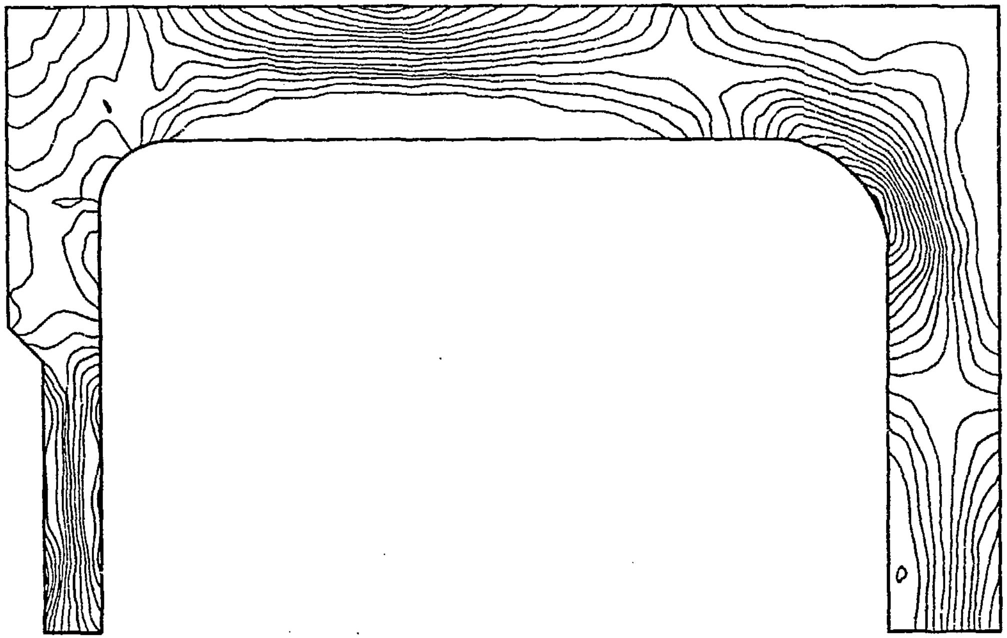
IN-PLANE LOADS FOR NORMAL OPERATING CONDITIONS

POLOIDAL FIELD COILS RESULTANT TORSIONAL LOADS

FAULT CONDITION NET TANGENTIAL AND INWARD RESULTANTS

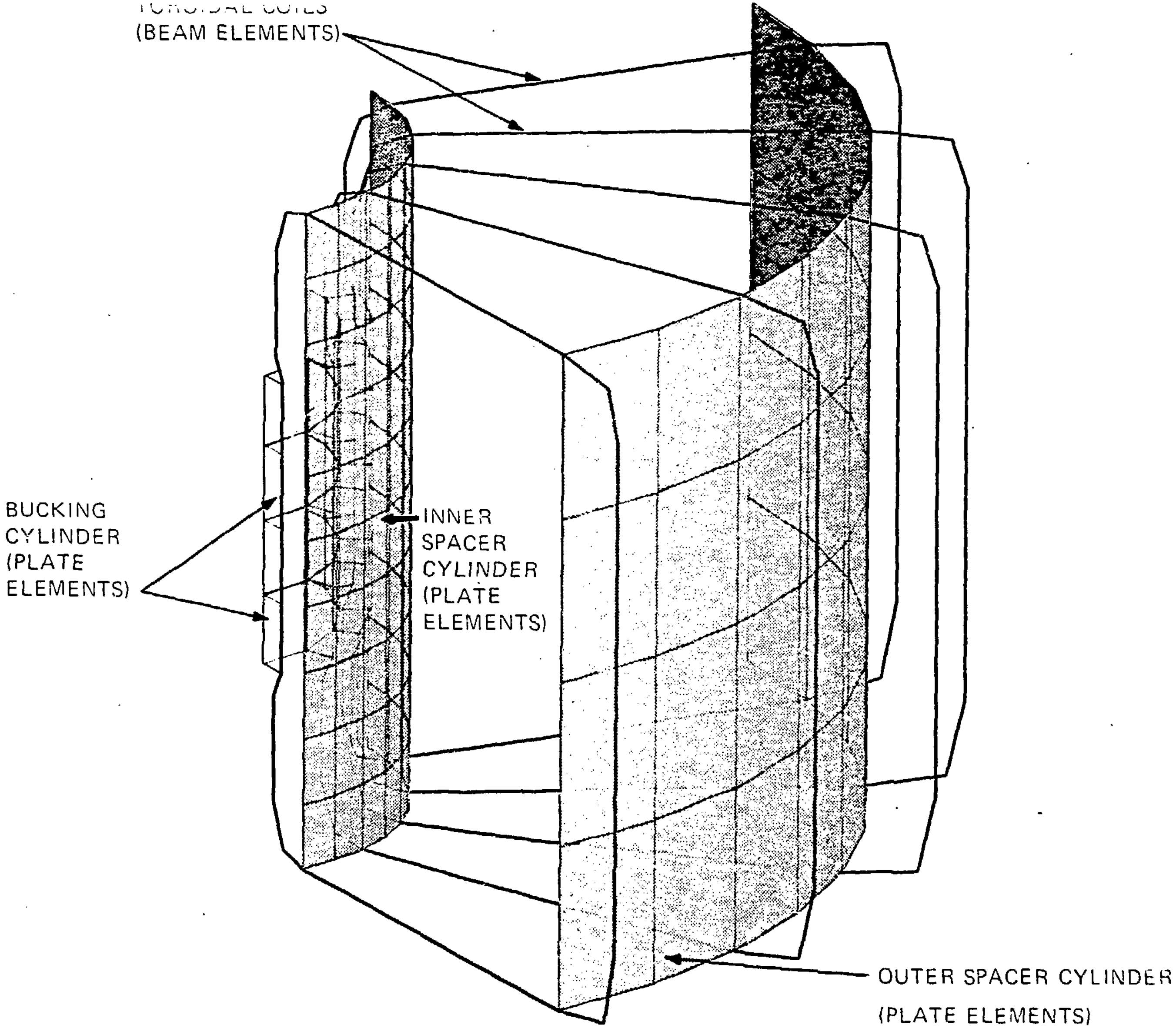
RESULTANT LOADS

FIG 2



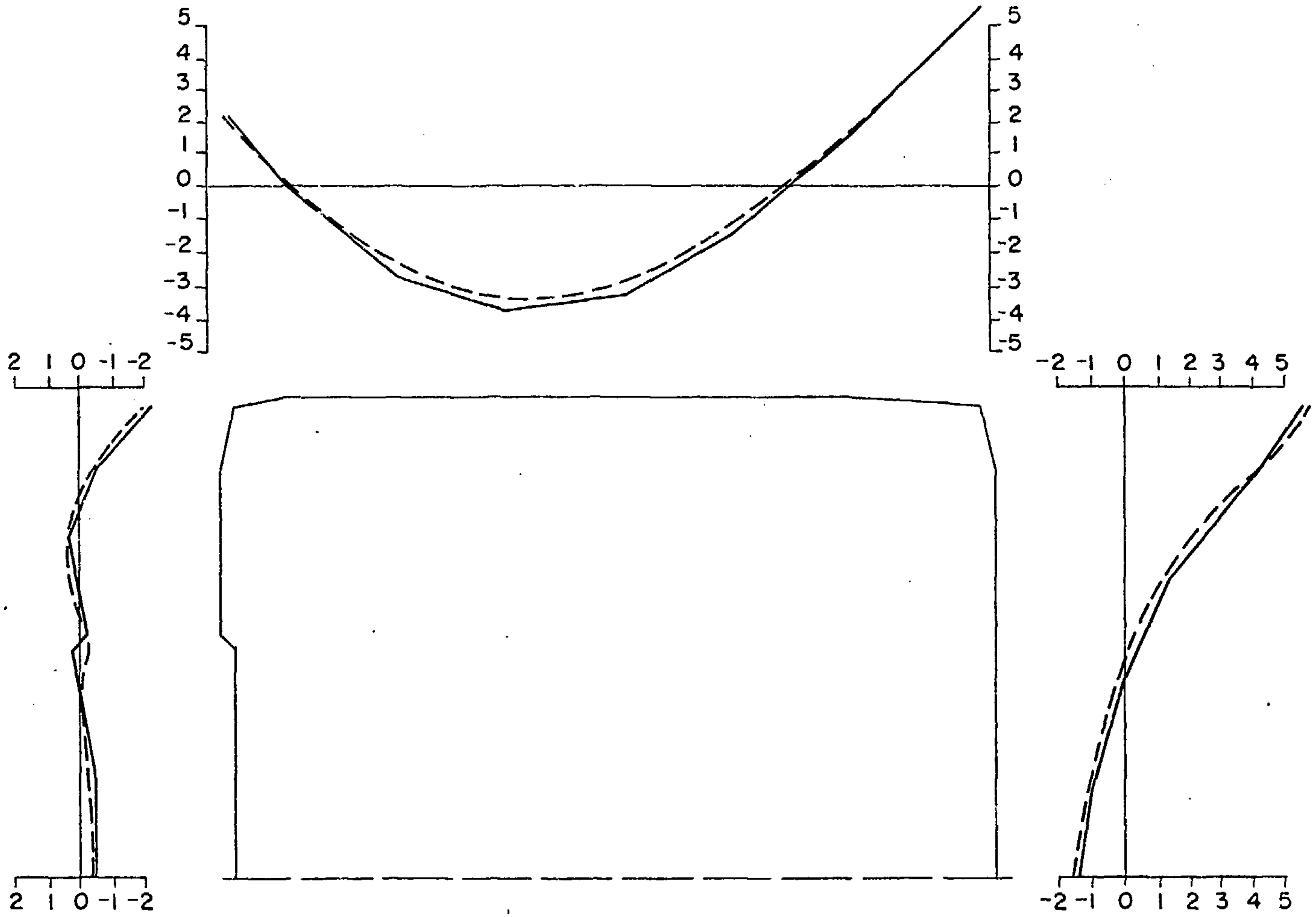
MAXIMUM STRESS CONTOURS

FIG 3



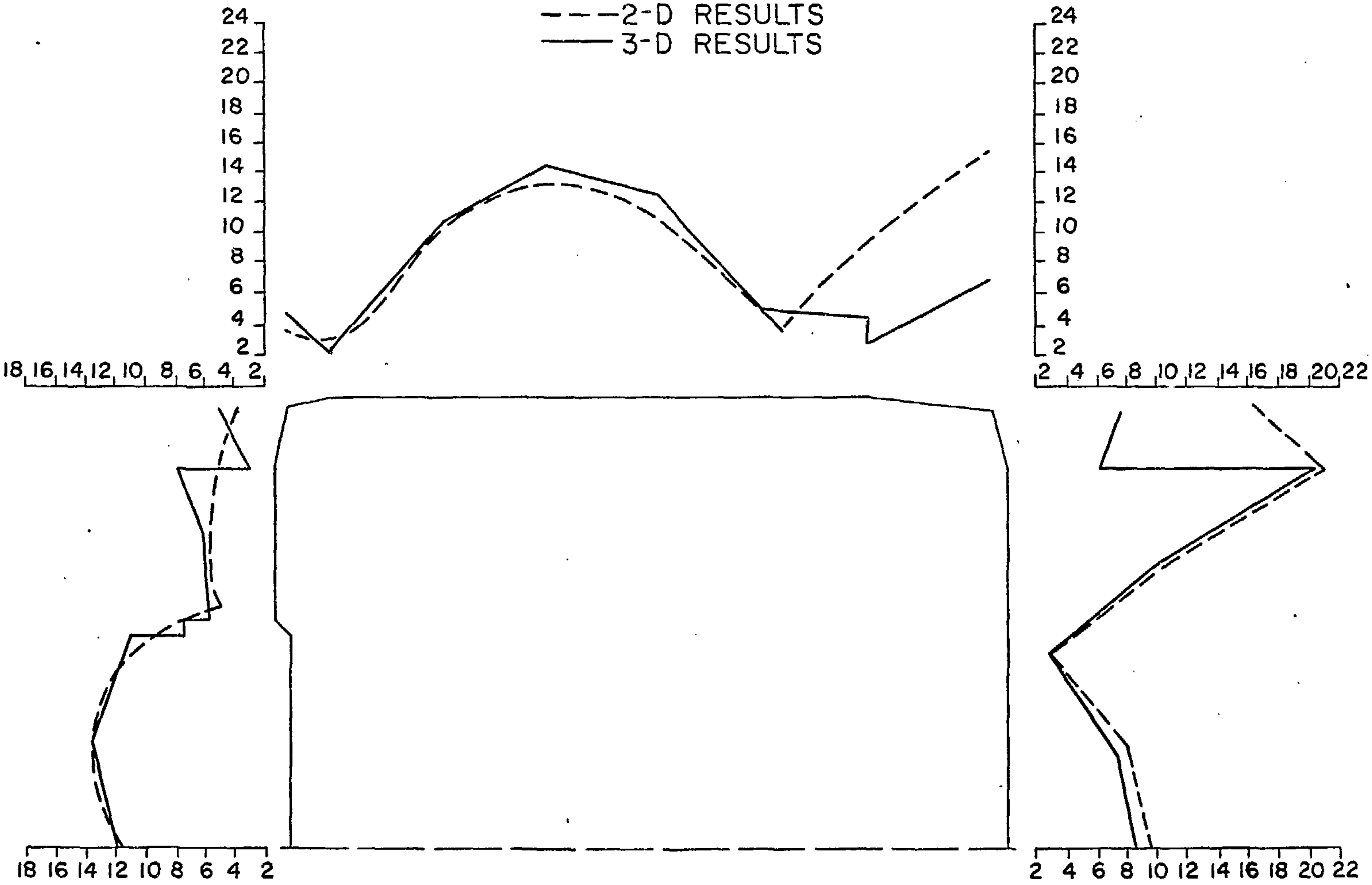
3-DIMENSIONAL FINITE ELEMENT QUARTER MODEL OF ISX

FIG 4



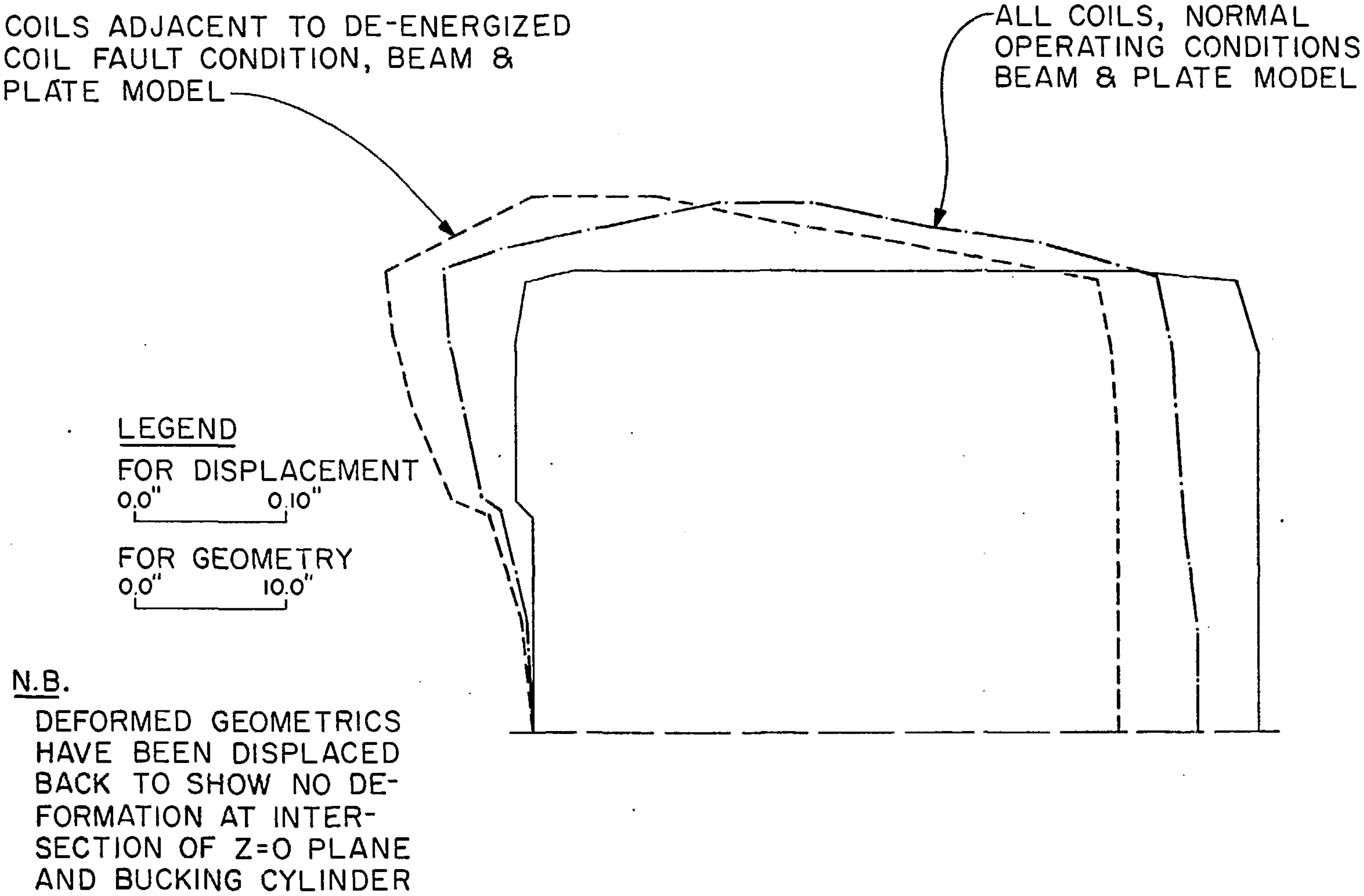
IN-PLANE BENDING MOMENT (10^6 IN. LB)
NORMAL OPERATING CONDITIONS

FIG 5



MAXIMUM ABSOLUTE STRESSES IN COILS (PSI X 10^3)
NORMAL OPERATING CONDITIONS

FIG 6



COILS ADJACENT TO DE-ENERGIZED COIL FAULT CONDITION, BEAM & PLATE MODEL

ALL COILS, NORMAL OPERATING CONDITIONS BEAM & PLATE MODEL

LEGEND

FOR DISPLACEMENT

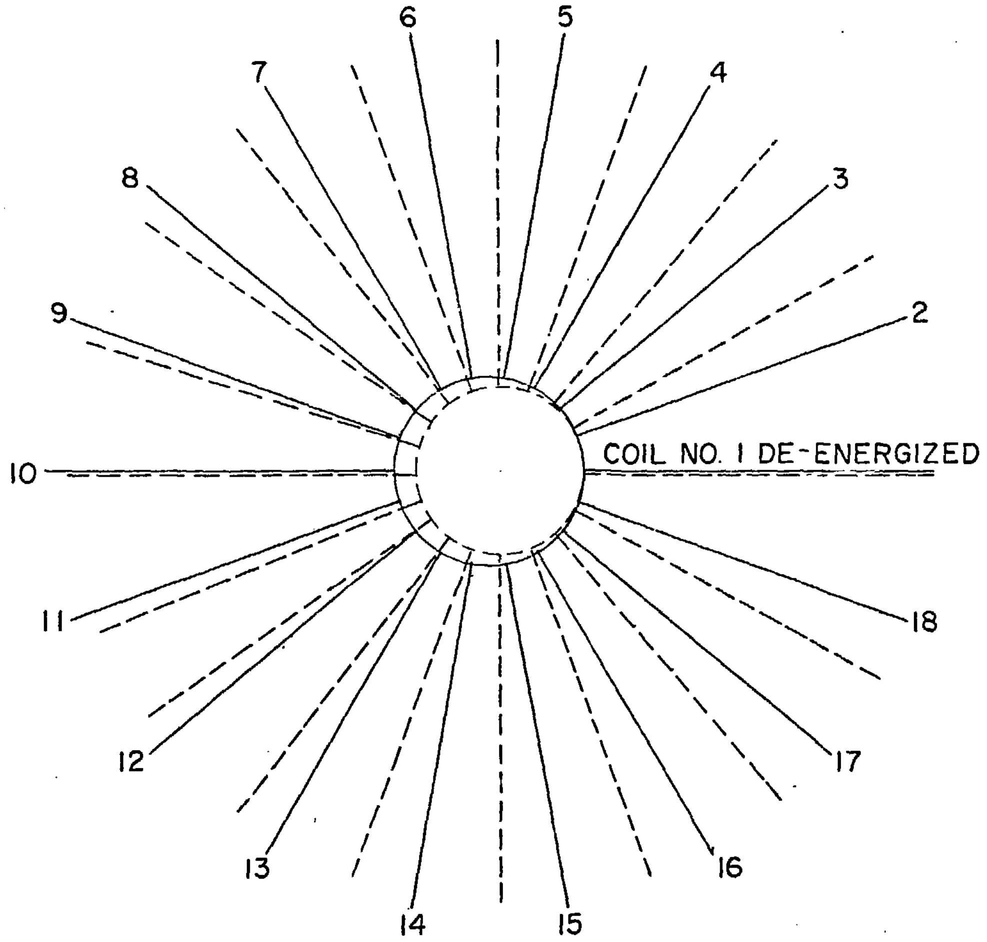
FOR GEOMETRY

N.B.

DEFORMED GEOMETRICS HAVE BEEN DISPLACED BACK TO SHOW NO DEFORMATION AT INTERSECTION OF Z=0 PLANE AND BUCKING CYLINDER

DISPLACEMENT OF COIL CENTERLINE

FIG 7



DISPLACEMENT OF COILS DURING FAULTED CONDITION

FIG 8