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AXISYMMETRIC STRUCTURAL SIMULATION OF THE CENTRAL SOLENOID FOR THE BURNING PLASMA EXPERIMENT (BPX)

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Abstract

The structural design and analysis of the BPX Central Solenoid is presented. The large-scale structural behavior of the solenoid is simulated with a two-dimensional (2-D) axisymmetric ANSYS[1] finite element model. The computer model is used to determine the time-dependent stress history in the coils and tie rods, and to perform various structural performance studies. Some of these studies are included here such as tie-rod preload optimization, relative movement at low-friction surfaces, alternate material and transient cool down effects. The results of these simulations are presented and discussed. A fatigue analysis of the conductor stresses is presented based on the BPX design criteria[2] and preliminary material property data. The relationships between the 2-D solenoid model and more detailed 3-D models of sub-components are also discussed.

Introduction

The function of the BPX poloidal field (PF) coil system is to produce the flux swing required to induce the current in the plasma and the field characteristics necessary to shape and control the plasma position. The PF coil system consists of ring coils, internal control coils and a five-coil central solenoid. At about 120 metric tons, the central solenoid represents the heart of the PF coil system. Of all the PF coils, the central solenoid presents the most challenging engineering problems. In essence, it must withstand large electromagnetic (EM) forces, high stresses and significant thermal transients for thousands of cycles. In addition, cost and size requirements demand an aggressive coil design.

Design and analysis are closely coupled in the development of the central solenoid. And an important part of the analysis requires an accurate estimation of the solenoid's forces, stresses and displacements. Finite element analysis (FEA) has brought speed and flexibility to the engineering process, and provided a means of exploring and evaluating the details and characteristics of the structure.

This paper presents a review of the 2-D axisymmetric model and analyses as they apply to designing the BPX central solenoid. The purpose of the model is to capture the global structural behavior of the solenoid, and to evaluate the effects of variations in structural components, materials, low friction surfaces, and thermal transients. The general purpose ANSYS computer code is used to perform these analyses.

The 2-D Axisymmetric Model

The central solenoid is predominantly axisymmetric in form. The beryllium copper (BeCu) conductor is waterjet cut from plate stock forming a circular current path three-quarters of the way around the coil. A "transition region" spirals out from one "conductor turn" to the next over the remaining 90° segment, thus defining the most significant variation from axis symmetry. Other major structural components such as covers, coil-to-coil shims and terminal support plates are also predominantly axisymmetric except for subtle machining details. Even the effects of the ten 140 mm (5½") diameter tie rods can be approximated by an equivalent ring of similar tensile area. Figure 1 shows a plot of the FE model.

1

Modeling Details

The top-bottom symmetry in the structure and normal operating loads allows modeling only the top half of the solenoid. A mathematically equivalent structure is achieved by assigning a vertical constraint to the nodes which lie on the symmetry plane. This approach shortens the computer run-time and increases the efficiency of the analyses with no sacrifice in the quality of the results.

Although the actual coil is a matrix of conductor plates, insulation and cooling channels, the use of the mixture rule is an accepted practice[3] in creating an equivalent smeared orthotropic material. However, care must be taken in evaluating stress results. The stress in the smeared material must be scaled at the component level to obtain the stress in the conductor. Scaling stress results is revisited in the Coil Stress History and Fatigue Analysis section.

The ten tie rods are modeled as a ring whose mean radius is the same as the tie rod bundle (273 mm), and whose build yields the same tensile area (0.1535 m^2).

The top cover is modeled as a stainless steel circular plate. However, the elastic modulus is reduced for elements in the region where tie rods, leads, and cooling channel penetrations diminish the stiffness of the structure. The thickness of the plate is modeled as the average of the top and bottom covers.

Directly below the cover is a 178 mm thick G-10 disk which is designed to produce a fairly smooth and uniform vertical stress distribution at the top of the PF3 coil.

The structure which occupies the vertical space between the PF coils is designed to satisfy many structural requirements. Figure 2 is a close-up view of the terminal detail, including the inter-coil shim region. A 4 mm thick G-10 disk is epoxied to the end of the PF coil and provides a ground plane for the 3/8" BeCu terminal support plate. The plate material is chosen to provide cool down displacements comparable to those of the adjacent coil. Next to the support plate is a low-friction slip plane which allows adjacent coils to move relative to each other without inducing excessive shear stresses. Finally, a G-10 shim fills the remaining space in between slip planes. In the actual design, radial grooves are machined into the terminal support plates and G-10 shims to assure concentricity during the current pulse. All low-friction slip planes are modeled with gap elements and a friction coefficient of 0.1, as demonstrated in Ref. 4.

Model Loading

The loads on the model consist of an initial tie rod preload, time-dependent coil and structure temperatures and EM conductor forces. Electromagnetic forces are calculated for six time points of the current pulse, and distributed over the 10 by 10 nodal point grid of the PF coils.

A typical service cycle of the central solenoid begins with a preload condition achieved by defining an initial strain across gap elements between the end of the tensile "shell" and the cover. The initial preload is followed by a slow cool down to 77°K, a six-point EM transient consisting of Preblip, Null, Start of Flat Top (SOFT), End of Flat Top (EOFT), End of Plasma Current Pulse (EOCP) and End of PF Current Pulse (EOP), a worst-case transient cool down gradient (TCDG) time point, and a return to 77°K. A variation from this load history is one in which the solenoid returns to room temperature, such as for a maintenance outage.

2

The coil temperature history is obtained from the current wave form analysis of Ref. 5 and indicates that the PF1 coil reaches a maximum temperature of 254°K. However, the cool down gradient is a variable in this analysis. In fact, one of the objectives of the analysis is to establish a cool down design specification.

Analysis

The primary objective of the finite element model is to estimate the stress history in the coils and tie rods. A major design objective is to assure that the structural integrity of the solenoid remains intact for the given load history over the design life of the machine.

The basic concept is to design a structure which exhibits linear elastic behavior everywhere except at the low friction slip planes. Conductor pancakes will be insulated, epoxy impregnated, and joined together electrically and mechanically to create a monolithic coil structure. However, excessive shear stress in the insulation, pancake-to-pancake vertical tensile stress, high strains in the coils and at the terminals, EM forces and transient cool down effects all threaten the structural integrity of the coils and therefore, their effects need to be evaluated.

Tie-Rod Preload Optimization

The tie-rod preload is a critical design parameter since it is the primary means of controlling the stack of pancakes which makes up the central solenoid. Optimization of the tie rod preload requires satisfying two design criteria; (i) the shear stress in the coil insulator must be within the allowable as defined by the project's design criteria document, and (ii) the vertical stress in the coil must remain compressive at all times.

The results of the tie-rod preload optimization study is summarized in Fig. 3. The analysis shows that the shear margin criterion is satisfied by a minimum preload of about 110 MN. This level of preload also assures pancake-to-pancake compression for cool down gradients below 8°K/turn. However, for a gradients above 8°K/turn, the tie-rod preload must be increased. The design basis cool down gradient is 10°K/turn, which requires a tie-rod preload of above 128 MN. Setting the tie-rod preload to this level also has the advantage of adding some margin between the calculated shear stress and the shear allowable.

Coil Stress History and Fatigue Analysis

The highest stresses in the central solenoid occur at the inside diameter and mid-height of the PF1 coil. Here, the large alternating hoop and vertical compressive stresses produce the biggest Tresca stress (or stress intensity) range. The free surface require that the shear stresses go to zero. And as a result, the three directional stresses become the three principal stresses. The smeared finite element stresses are scaled by the packing fractions to account for the volume fraction of conductor and insulation. Packing fractions are calculated based on the number of turns, the coil build, and the insulation thicknesses. These values for the BPX central solenoid are:

$$PF(radial) = 0.869$$
$$PF(vertical) = 0.952$$

PF(hoop) = 0.827

The stress in the conductor is obtained by dividing the smeared stress components by the appropriate direction-specific packing fractions. In addition, the hoop stress is increased another 3% to account for the uncertainty in the analysis[6].

This data manipulation is automated by the ANSYS POST26 post processor for the maximum stress location of the PF1 coil. The shear stress, $\frac{1}{2}(\sigma_i - \sigma_j)$, is calculated for all time point and for each of the three 45° maximum shear planes. The highest stress values occur on the two planes which include the hoop component. Of these two planes, the largest stress intensity range occurs on the vertical-hoop plane, since the large compressive vertical stress contributes more to the stress intensity than the near zero radial stress. The stress history plot for the vertical-hoop shear plane is shown in Fig. 4 and is based on a 10°K/turn TCDG and 128 MN preload.

The cyclic nature of the machine's load history requires that an analysis to estimate the fatigue life of the central solenoid coils. The project's design criteria outlines the procedure used to perform this fatigue analysis. Alternating shear stresses are converted to shear stress ranges $\Delta\tau$, which determines the allowable number of cycles (N) based on the preliminary design basis fatigue curve for high strength BeCu conductor:

$$\Delta\tau = 4964\ (N)^{-0.55} + 246\ (N)^{-0.0862}\ [MPa]$$

Dividing the actual number of cycles (n) by the allowable number of cycles gives the usage factor (U) for a particular stress range. Summing usage factors for all stress pairs yields the cumulative usage factor (CUF), which must be less than one. This calculation indicates acceptable fatigue results for the worst shear stress plane (Hoop - Vertical), as summarized in Table 1.

The principal stress history at the maximum stress location is input data required to perform a crack growth evaluation. The directional stresses, augmented by the packing fractions and the 3% uncertainty factor, are shown here in Fig. 5.

Hoop stress is by far the largest stress component in the central solenoid. This is illustrated by the time-dependent stresses previously discussed and shown in Fig. 5. Figure 6 is a plot of the hoop stress distribution in all three PF coils at Preblip.

Tie Rod Stress History

The analysis of the baseline configuration also produces stresses in the equivalent tensile elements. These stresses can be interpreted as the nominal stress in the tie rods as the results do not include the intensification which occurs at the tie rod threads, or from bending caused by a cover plate rotation.

The nominal tie rod stress history is shown in Fig. 7. Notice that the stress range of 326 MPa, important to the fatigue life of the tie rods, is set by the difference between the Preblip (486 MPa) and the EOP (812 MPa) stress states. At Preblip, the large EM loads cause axial compression in the coils which relieves some of the tie rod preload. At the EOP, the coils are at their hottest condition which causes a large tensile stress condition. The only greater tie rod

4

stress state is the initial solenoid preload case, when the tie rod stress is 840 MPa.

Relative Motion at Low Friction Surfaces

The central solenoid is designed to accommodate independent relative motion between adjacent coils. This is achieved by incorporating low friction surfaces which separate each coil from it's neighbor, and PF3 from the cover. This freedom of motion is important since each coil has its own EM force and thermal expansion strain history. Relative motion is on the order of 1 mm. Imposing displacement compatibility between adjacent coils would raise shear stresses by about 8 MPa, requiring a 20% increase in the tie-rod preload. An additional benefit of providing low friction slip planes is that they add flexibility to the electromagnetic design.

Effects of Alternate Materials

The 2-D model is also used to evaluate the effects of varying the material of a given component. For example, an evaluation is made to determine the effect of using stainless steel instead of beryllium copper for the terminal support plate. The analyses show that a turn to turn tensile stress of 15 MPa is developed at cool down with a stainless steel terminal support plate. Radial stresses are reduced to 6 MPa by making the plate beryllium copper. This is simply due to the thermal contraction compatibility between the coil and BeCu. Stainless steel contracts at a slower rate, and the conductor turns are pulled apart as the solenoid cools to 77°K.

Another example of using the 2-D model to evaluate material property changes involves replacing the baseline inconel tie rods with BeCu. The BeCu tie rod analysis has an insignificant impact on coil stresses, but shows a reduction in the required preload (104 MN compared to 128 MN) and alternating stress range (238 MPa compared to 326 MPa) when compared to the inconel tie rod analysis. This is because the expansion rate of the BeCu tie rods match that of the coil better than inconel. In addition, the lower elastic modulus for a fixed strain range results in a lower stress range. However, the capability of BeCu to survive in this stress history has not been evaluated.

Integration of 2-D & 3-D Component Models

The 2-D model is the basis of the central solenoid design process. In addition to determining the optimum tie-rod preload, calculating the coil and tie rod stress histories, estimating relative motion across low friction surface, and evaluating the effects of different material properties, the 2-D model serves as a source of input for many other finite element analyses. The stresses and displacements establish boundary condition for such 3-D analyses as inside and outside joints, interpancake cooling channels, cover plates, tie-rod threads, terminals, lead supports, and low-friction surfaces. And in return, some of the detailed analyses results are feed back into the 2-D analysis to create a more accurate model. For example, the detailed analysis of a double pancake[6] establishes a shear stress component and an increase in the conductor hoop stress based on 3-D effects. These effects are included in the shear margin and alternating stress history calculations presented in the section on Coil Stress History and Fatigue Analysis.

Conclusions

This analysis concludes that a 2-D axisymmetric finite element model is an efficient and effective means of simulating the global behavior of the BPX central solenoid. The model runs quickly, and provides a means of performing preload optimization, conductor and insulation shear stress evaluation, component sizing, optimization of material selections, and boundary condition requirements for more detailed analyses.

Preliminary results indicate that the conductor stresses pass the fatigue requirements, and insulation shear stresses are also within allowables when the tie rod preload is kept at or above the calculated minimum value of 128 MN. Cool down gradients must be limited to 10°K/turn, otherwise the required tie-rod preload becomes large, or vertical tensile stresses at cool down will begin to produce insulation failures.

References

[1] ANSYS Revision 4.4A, Swanson Analysis Systems, Inc., Houston, PA

[2] "BPX Magnet Structural Design Criteria," Princeton Plasma Physics Laboratory, F-910208-PPL-03, Rev. 0, February '91

[3] "Stresses in Superconducting Solenoids," E.S. Bobrov and J.E.C. Williams, Francis Bitter National Magnet Lab, MIT, ASME Mechanics of Superconducting Structures, AMD - Vol. 41, November, 1980

[4] "Evaluation of Low Friction Materials for the Central Solenoid of the Compact Ignition Tokamak (CIT)," B.A. Smith, Z. Piek, P. Thomas, R. Vieira, Proceedings of the Ninth Topical Meeting on the Technology of Fusion Engineering, Oak Brook, Ill., October 7-11, 1991, Published by Fusion Technology, May 1991 - Vol. 19, No. 3, Part 2A

[5] MIT Plasma Fusion Center BPX Project technical paper number GEM-59, "The P7 PF Coil Set and the PF Current Waveforms for the 11.8 MA, 100 MW Double Null Divertor for the 2.61 m Machine for BPX," R.D. Pillsbury, Sept. 17, 1991

[6] "Nonaxisymmetric Behavior of the Central Solenoid Spiral Cut Pancakes for the Burning Plasma Experiment," Peter H. Titus, presented at the 14th IEEE/NPSS Symposium on Fusion Technology, San Diego, CA, October, 1991

Table 1: Fatigue Analysis of the PF1 Conductor

Load Range	$\Delta\tau$ (MPa)	n (cycles)	N (cycles)	U n/N	CUF= ΣU $\leq$1.0
EOFT to TCD	287	3,000	9,600	0.31	0.38 (OK)
Preblip to Null	225	3,000	42,000	0.07	

Stainless Steel Cover

G-10 Shim

Equivalent Tensile
Shell

PF3

PF2

See Fig. 2 for
Inter-Coil Details

PF1

Plane of Symmetry
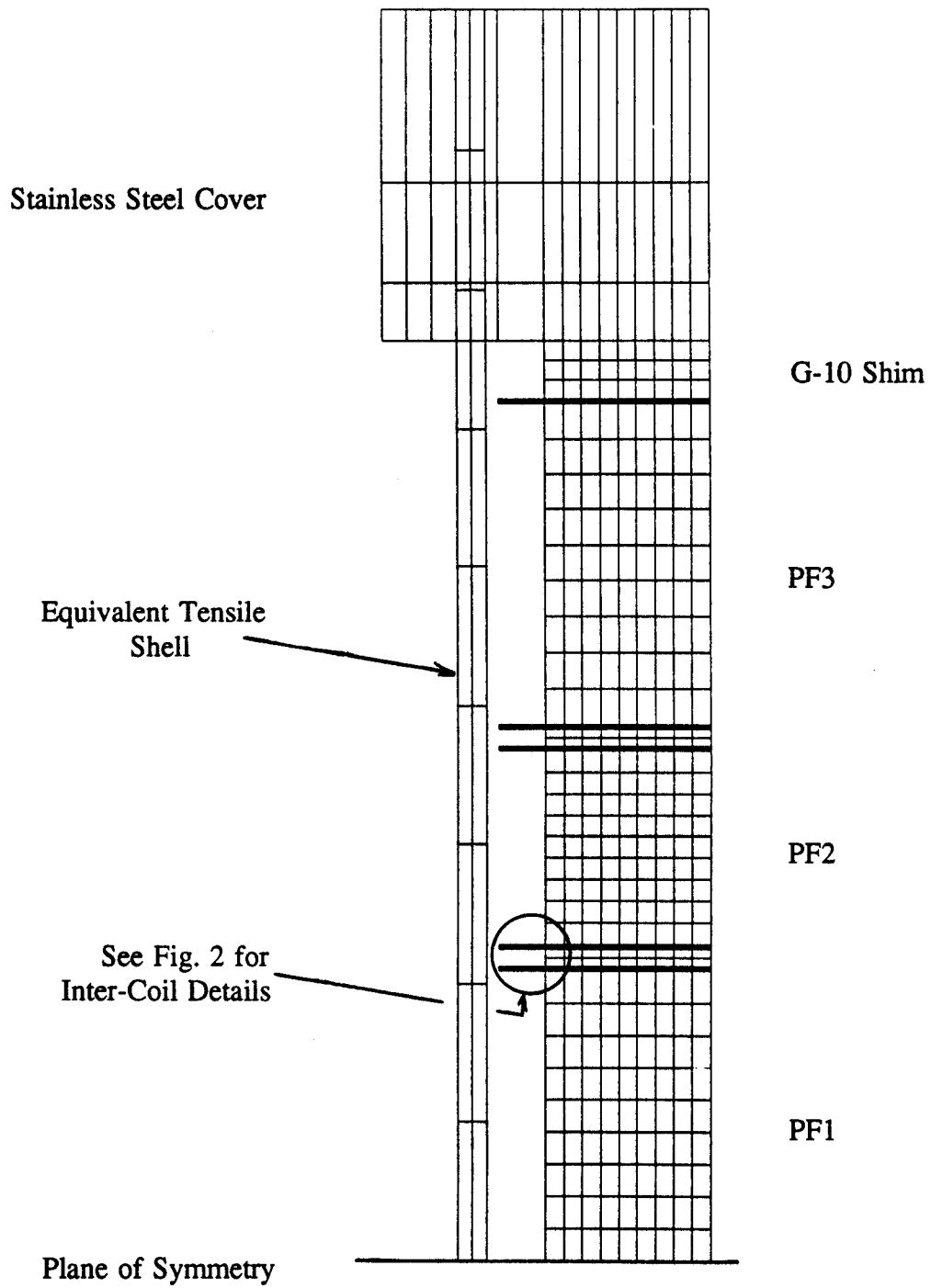
Fig. 1 Element Plot of the 2-D Axisymmetric Model
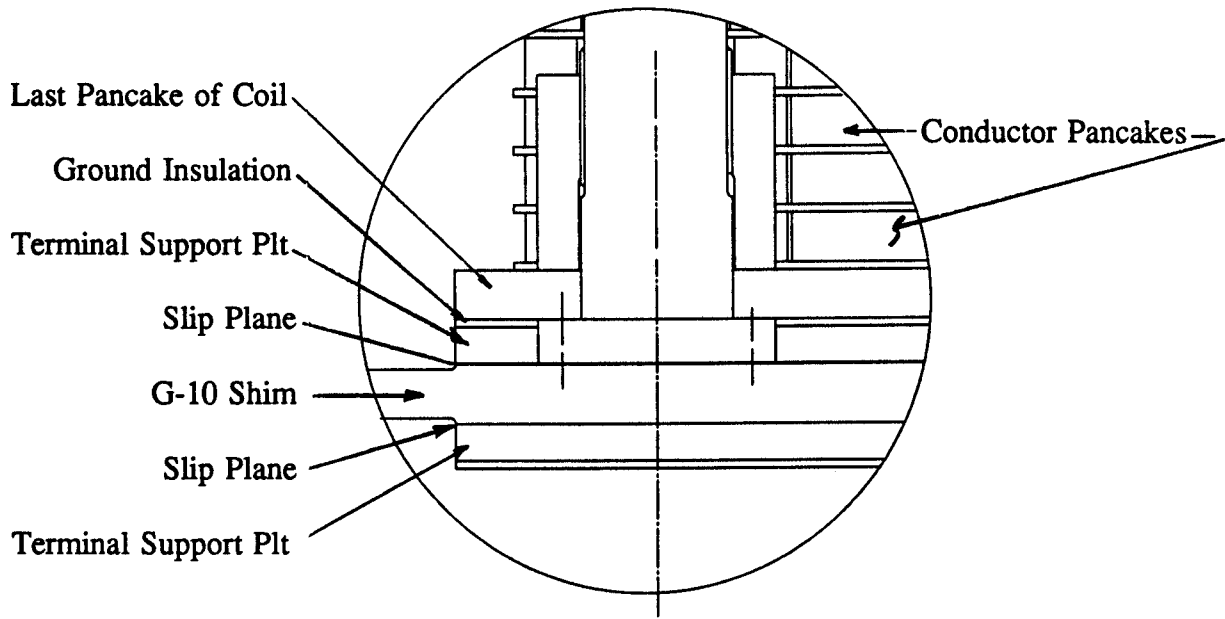
Fig. 2 Detail of Terminal and Inter-coil Shim

Turn-to-Turn Cool Down Temperature Gradient, °K/turn
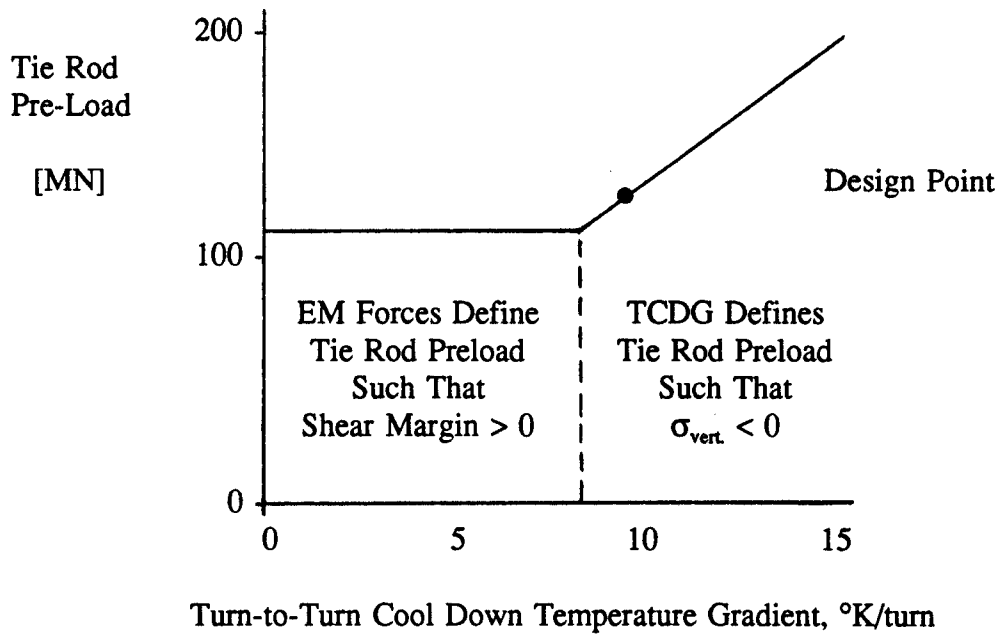
Fig. 3 Minimum Tie Rod Preload Requirements
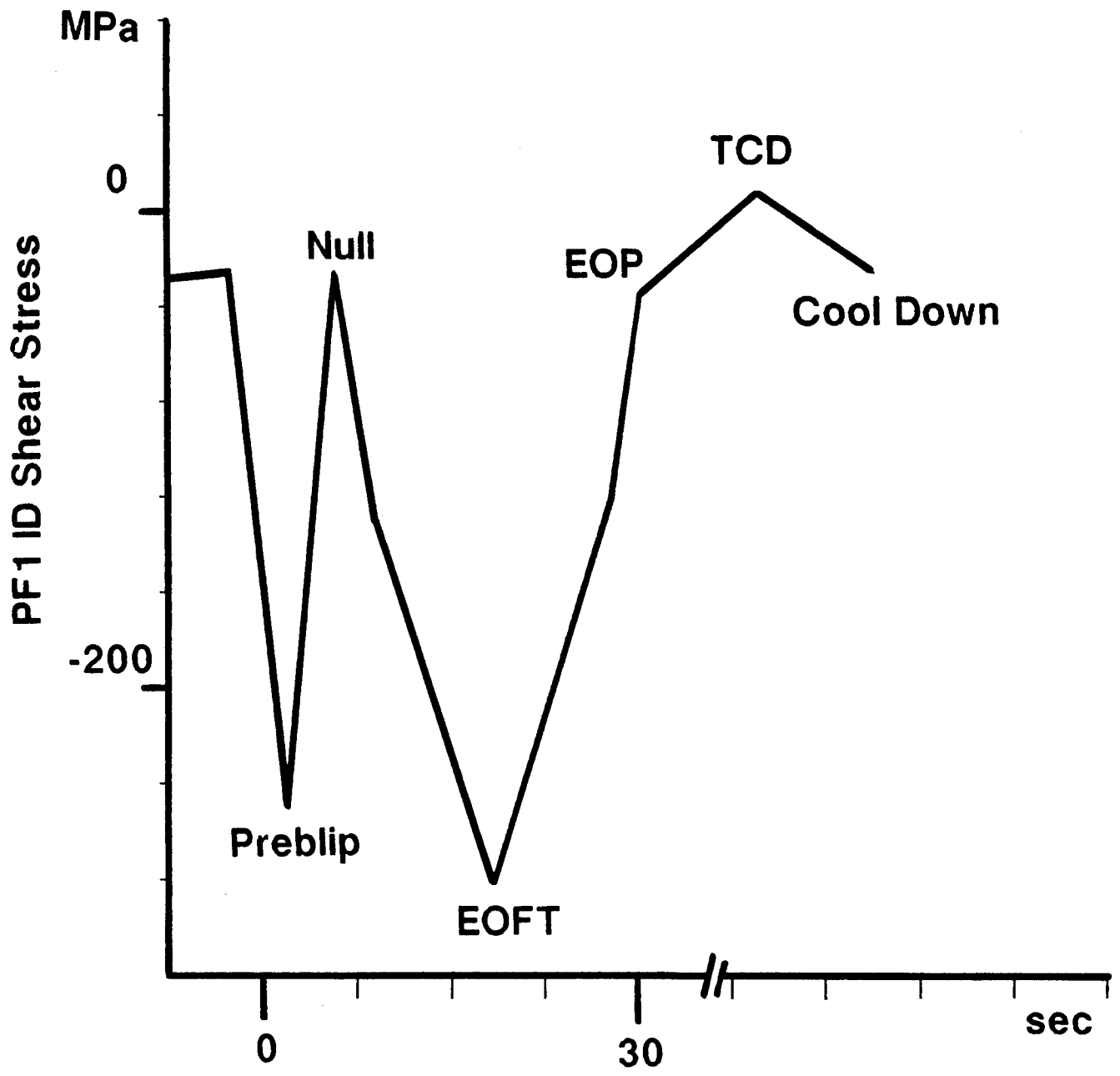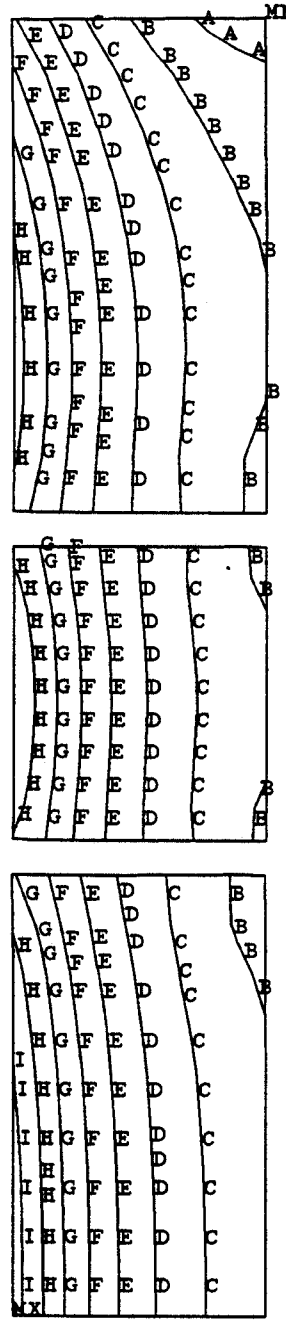
Fig. 4 PF1 Maximum Shear Stress History, MPa
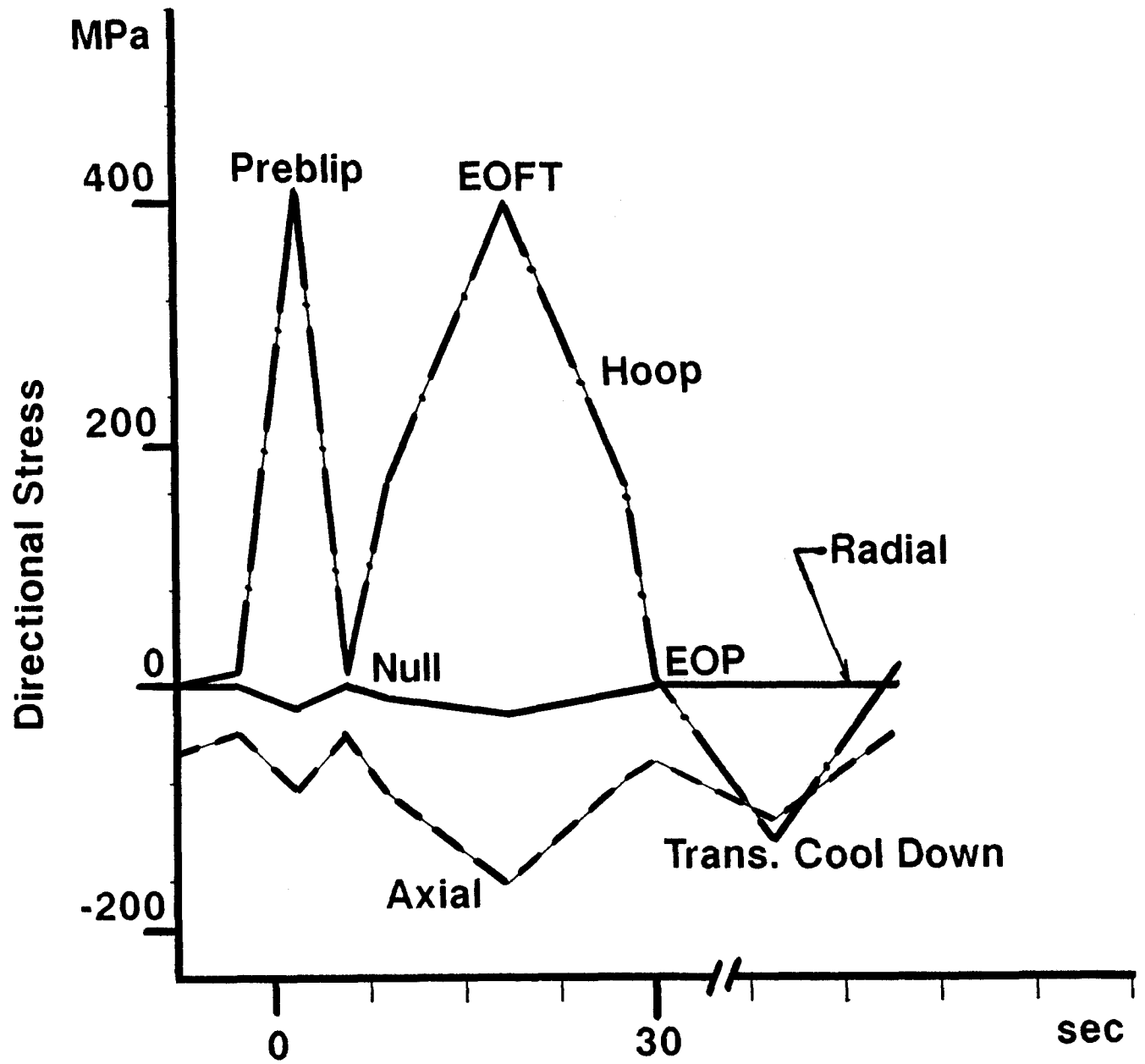
Fig. 5 PF1 ID Directional Stress History, MPa

Min = 115 MPa
A = 132
B = 165
C = 199
D = 232
E = 264
F = 297
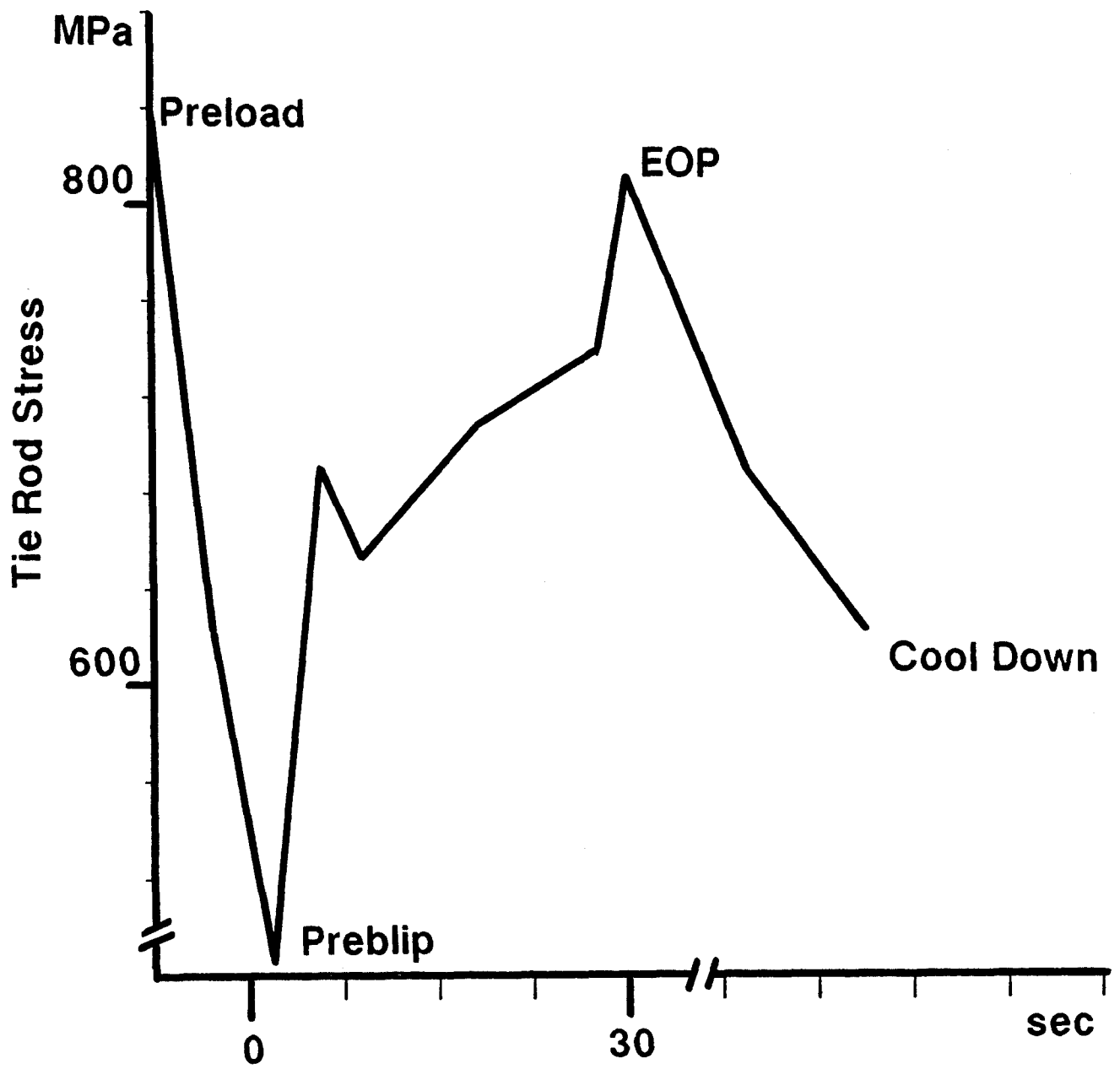G = 330
H = 363
I = 396
Max = 414

Fig. 6 Hoop Stress Distribution in the PF Coils at Preblip

Fig. 7 Nominal Tie Rod Stress History, MPa