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Structural Analysis Of A Superconducting Central Solenoid For The Tokamak Physics Experiment

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Abstract — The **Tokamak Physics Experiment (TPX) concept design uses superconducting coils to accomplish magnetic confinement. The central solenoid (CS) magnet is divided vertical into 8 equal segments which are powered independently. The eddy current heating from the pulsed operation is too high for a case type construction; therefore, a "no case" design has been chosen. This "no case" design uses the conductor conduit as the primary structure and the electrical insulation as a structural adhesive. This electrical insulation is the "weak link" in the coil winding pack structure and needs to be modeled in detail. A global finite element model with smeared winding pack properties was used to study the CS magnet structural behavior. The structural analysis results and peak stresses will be presented.**

I. INTRODUCTION

The structural analysis of the Tokamak Physics Experiment (TPX) Central Solenoid (CS) (see Fig. 1) includes analysis of the support structure as well as the winding pack structure. The winding pack consists of cable-in-conduit conductor wrapped with a glass wrap insulation and separated by a polyimide sheet. The entire winding pack is wrapped with ground plane insulation. In order to simplify the analysis of the central solenoid, the complex winding pack structure is approximated as an orthotropic material or "smeared" mechanical properties. The "smeared" mechanical properties were calculated from a finite element model of the conduit and insulation [1].

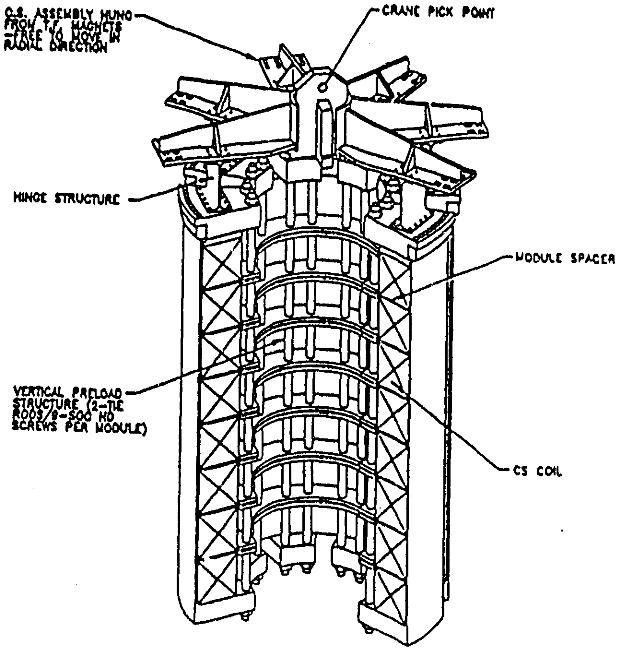

Fig. 1 Central solenoid assembly.

The finite element method was chosen for this analysis because the availability of commercial computer codes for simulation of magnetics, thermal, and stress problems. The analysis was carried out with ANSYS [2], a finite element analysis code. First, a magnetic analysis was completed to determine the Lorentz forces which were then used in the stress analysis.

II MODEL DEVELOPMENT

The central solenoid in TPX consists of 8 superconducting coil modules which are stacked vertically. The coil modules are wrapped in nominal 1/4 inch ground wrap insulation (glass and polyimide material) and separated by a 3/8 inch thick steel plate. The coils are held together by stainless steel tie rods on the inside diameter and plates on the outside diameter, see Fig. 1. The bolts and plate structure act as a pre-load structure, making sure the coils remain in compression during cool-down and operation. The top and bottom end caps are segmented to reduce eddy currents and are thick enough to act as rigid blocks. The I-beam hangers between the spider support and the top end caps have three functions: 1) to allow radial displacement of the top end of the coil, 2) to allow rotation of the top end of the coil, and 3) to support the coil stack-up dead weight. The main purpose of these hangers is to allow the coil to displace and rotate without generating bending stress in the coil near the top end cap, i.e. to approach a free end.

The 2-D axisymmetric model developed to analyze the central solenoid is shown in Fig. 2. The top end which is allowed to translate and rotate can be approximated as a free end. The bottom end is also a free end allowing top and bottom symmetry to be used. The model is used to estimate the stresses in the conduit, insulation, and support structure during cool-down and throughout the normal operation of the central solenoid. The difference in the thermal contraction between the Incoloy conduit and Stainless Steel support structure result in a pre-load on the winding pack. The analysis is done first without any pre-load or cool-down step to determine the stresses in the conduit and insulation which result from the Lorentz loading only. The model includes the winding pack which is represented with directional orthotropic material properties, the polyimide ground-plane insulation around the winding packs, and the 316 LN stainless steel spacers between adjacent winding packs. In addition, the 316 LN stainless steel pre-load support structure and the end caps are included in the model.

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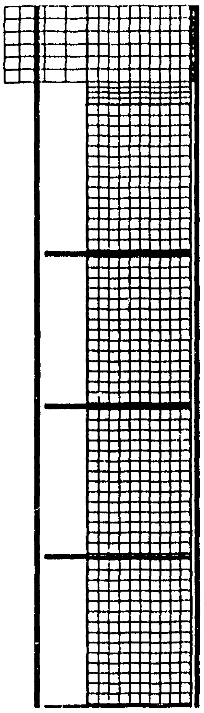

Fig. 2. 2-D axisymmetric mesh of the central solenoid.

The central solenoid is loaded through three mechanisms, thermally - during cool down, mechanically - through pre-load and magnetically - through Lorentz body forces. The central solenoid is cooled from room temperature down to 4 K, a delta of 289 K, and then remains at 4 K for months at a time. The pre-load is applied to insure that the coils remain in compression, more specifically, that the conductor insulation will never be in tension perpendicular to the lay of the cloth. The Lorentz forces are calculated from a magnetics model which includes all of the PF coils and the plasma. The PF coil geometry and coil currents are inputs into the magnetic model[3]. The pre-load structure pretension is obtained in the model by defining a level of pre-strain (mm) to the ends of the tie-rods and support plates.

III RESULTS

The Lorentz forces calculated in the magnetic analysis are shown in Fig. 3 for 5 time steps (Prebias, Start of Flattop SOF, Start of Burn SOB, End of Burn EOB, and End of Flattop EOF) corresponding to one machine cycle. The radial Lorentz burst force in the coils result in a hoop tension in the conduit. The vertical Lorentz forces sum down the length of the coil and are maximum at the mid-plane of the coil (PF 1). A plot of vertical force as a function of time is show in Fig. 4. PF 1 is at the center of the CS coil and PF 4 is located at the top. At t=5.0 (Prebias) there is a net downward vertical force of 6.6 MN which will causes a horizontal gap to form between PF 4 and the support structure. At t=9.0 (SOF) there is a net upward vertical force of 3.9 MN in PF 4 and a net downward force of 24.7 MN in PF 1-3 which will cause a horizontal gap to from between PF 3 and PF 4. The weight of the PF 4 coil is 0.02 MN which is 200 times smaller then the vertical upward force and does little to resist the gap formation. A pre-load is applied to the CS coils to eliminate the formation of a gaps during normal operation. In addition the pre-load is used to compress the coils and spacers together after assembly of the CS to eliminate any gaps resulting from manufacturing tolerances. A pre-load of 6.7 MN is obtained during cool-down from the difference in thermal contraction between the Incoloy conduit and the Stainless Steel support structure. Additional pre-load must be applied at room temperature to eliminate any assembly tolerance gaps between the coils and the spacers creating an integrated structure. However an increase in the pre-load also increases the vertical stress in the conduit and in turn increases its Tresca stress. The pre-load must be determined so as not to over-stress the conduit. The maximum pre-load allowed was determined

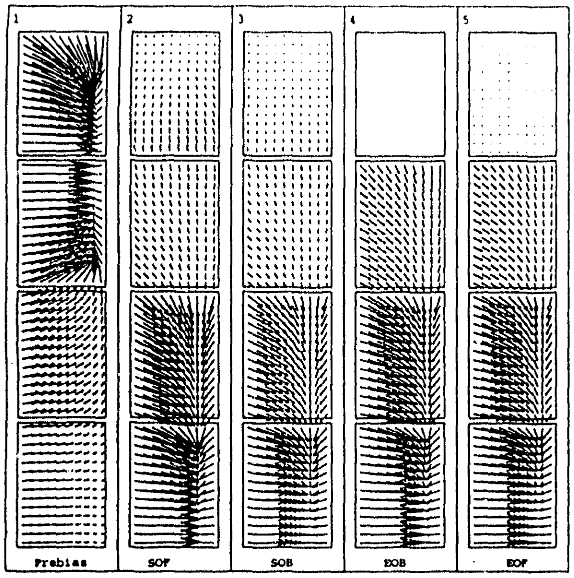

Fig. 3. Lorentz forces in the CS winding pack.

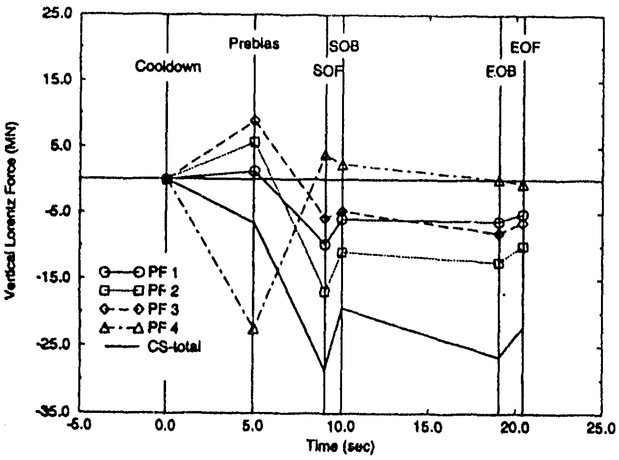

Fig. 4. Vertical Lorentz force in PF 1-4 coils during one machine cycle.

by two criteria: 1) the Tresca stress must be less then the static stress allowable for Incoloy (σ_{allow}=800 MPa[4]), 2) the stress intensity range (alternating Tresca stress) must satisfy the fatigue life requirements. The stress range does not change with an increase in pre-load because the alternating stress comes from the electro-magnetic loading. The magnet system will be thermally cycled from room temperature to 4 K a maximum of 300 times per the general requirements document [5], therefore an increase in pre-load will increase the stress intensity rang, however, the stress range is generally small and does little to effect the overall fatigue life. However, an increase in pre-load does increase the average stress and using (1) an equivalent stress intensity range (S_{eq}) can be estimated to include this effect [5].

$$S_{eq} = \frac{S_{alt}}{1 - S_{mean} / S_u} \qquad (1)$$

Where S_{alt} is the alternating stress, S_{mean} is the average stress, and S_u is the tensile strength. Fig. 5 shows that the pre-load does increase the stress intensity range . The base metal and weld metal allowables were estimated from the Tresca versus Time plot shown in Fig. 6 assuming one stress amplitude (neglecting the smaller stress deviations) and the fatigue life data presented in A. Nyilas et al. [6]. A pre-load greater then 35 MN will put the stress intensity range over the weld allowable, however, for the present load scenario a pre-load of 25 MN results in a Tresca stress of 790 MPa which is very close to the static allowable of 800 MPa. Depending on the load case either of the static allowable or the fatigue allowable will be the limiting one in determining the pre-load.

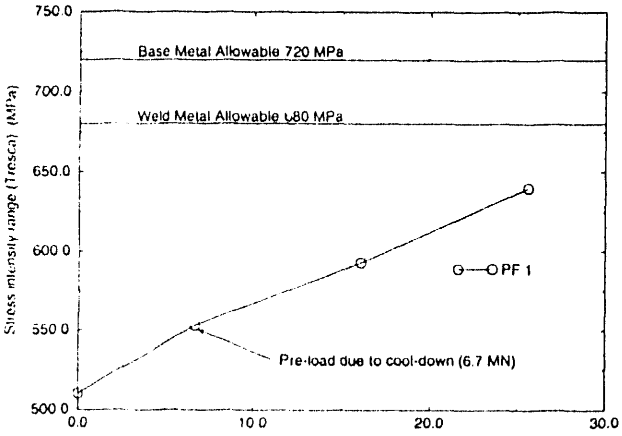

Fig. 5. Pre-load versus stress instensity range (S_{eq}) in the PF 1 coil

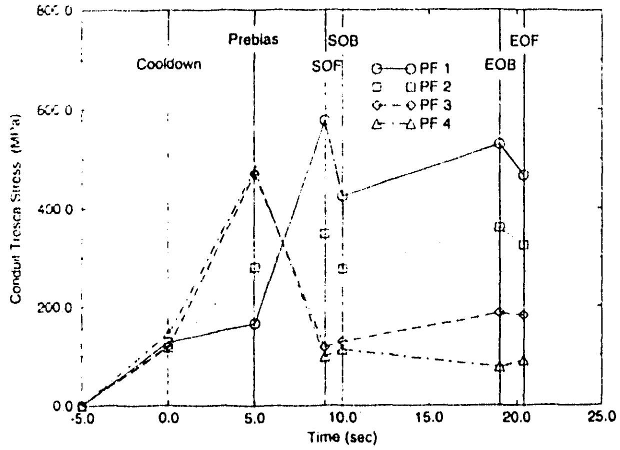

Fig. 6. Tresca stress in PF 1-4 coils during one machine cycle, includes a 6.7 MN pre-load obtained during cool-down

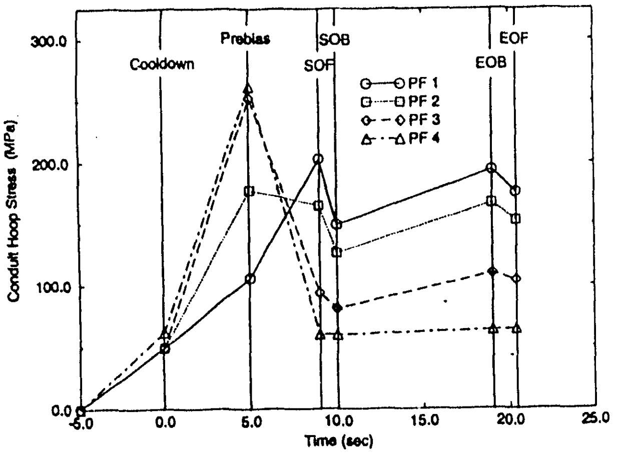

Fig. 7. Conduit Hoop stress in PF 1-4 during one machine cycle, including cool-down (2.4 times the winding pack stress)

Fatigue crack growth is controlled primarily by the maximum principle stresses. The vertical stress due to Lorentz forces and pre-load are in compression resulting in no crack growth. The hoop stress is in tension and is the main concern for fatigue crack growth. In Fig. 7 the hoop stress for each coil in the CS is plotted throughout one machine cycle including a cool-down cycle. Over the life of the tokamak the CS magnet system is required to cycle through 30,000 machine cycles and 300 hot-cold cycles [5]. Using the requirements in TPX Structural and Cryogenic Design Criteria Document [7] where the maximum permissible initial flaw size shall be governed by, as a minimum, two times the growth life experimentally determined based on component tests, or four times the growth life determined based on material tests. An initial flaw size of 5% of the thickness of the conduit (2.41mm) can be detected using an ultrasonic non-destructive test [8]. Base material properties can be used instead of weld material properties because the conduit in the CS can manufactured in lengths long enough that butt welds are not required. The maximum stress range is 210 MPa in PF 4. Using the 5% flaw size and the fatigue crack growth curves presented in R. Hoard et al. [9] for base metals a fatigue crack growth life of 2×10^6 can be determined. This easily satisfies the requirement that the fatigue crack growth life be four times the required life. The small deviations in the stress range experienced during cool-down and throughout one machine cycle have little effect on the overall life of the machine for the present load case. Under the present load conditions the fatigue crack growth stress range allowable is 400 to 425 MPa.

IV CONCLUSIONS

- A pre-load is necessary to eliminate the formation of gaps and ultimately keep the insulation in compression throughout the life of the CS magnet.

- A portion of the pre-load is obtained during cool-down from the difference in thermal contraction between Incoloy 908 and 316LN stainless steel.

- A maximum pre-load of 25 MN may be applied to the CS.

- The conductor performs adequately as the primary structure based on fatigue life and fatigue crack growth criteria.

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