Eddy Current Heating in the Cold Structure in TPX

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Abstract **- The toroidal field coil cases and support structure for the TPX are at cryogenic temperatures. The time varying currents in the poloidal field coil system will induce eddy currents in these structures. The associated Joule dissipation will cause local heating and require heat removal which will show up as a load on the cryogenic system. Knowlege of the heat load distribution in both space and time is important to the design of the system. Analyses have been performed using programs EDDYCUFF and ANSYS and the results presented.**

I. INTRODUCTION

The cases around the toroidal field (TF) coil and coil structural support system for the Tokamak Physics Experiment (TPX) [1] are at cryogenic temperatures. The plasma current is initiated and ramped inductively by the poloidal field (PF) system. The time dependent currents in the PF coils will induce eddy currents in the structure. The attendant Joule heating will show up as an additional load on the cryogenic system.

Fig. 1 shows an elevation view of the tokamak with the seven pairs of PF coils. The major radius of the machine is 2.25 m, the plasma current is 2 MA and the toroidal field is 4 T at the major radius. The plasma current is ramp in 4 seconds.

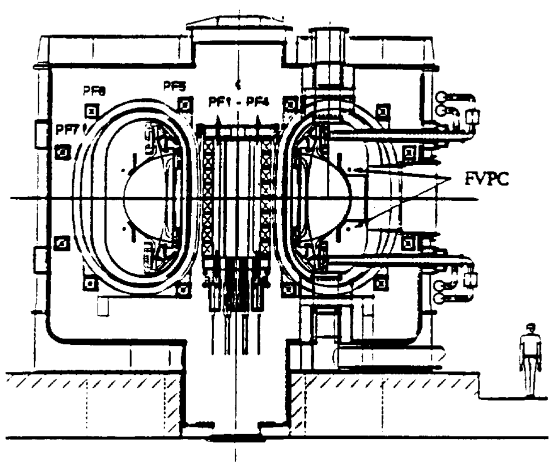

Fig. 1 TPX Elevation View

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A view of the structural components of the TF coil cold structure (TFCCS) is shown in Fig. 2. The major components of the structure are the TF coil cases, and two shells that join the individual TF coils together. The system has both insulated (bolted) and conducting (welded) joints in the outboard region. The bolted joints are every four coils making a quadrant. The inner legs of the TF coils are insulated every other coil. The three dimensional geometry of the structure mandates a three dimensional solution of the eddy current problem.

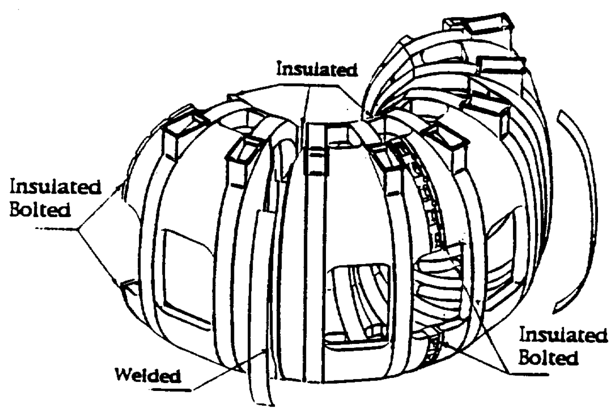

Fig. 2 TPX TF Coil Cold Structure (TFCCS)

JOULE HEATING ANALYSES

The 3-D, thin shell, eddy current program, EDDYCUFF [2], is used to determine the eddy currents and Joule losses in the TFCCS of TPX. EDDYCUFF models the conducting media as a thin shell which assumes a current density that is uniform through the thickness. The same program, EDDYCUFF, was used in [3] to calculate eddy currents in elements of the ITER (International Thermonuclear Experimental Reactor). However, the temperatures due to these eddy currents were not calculated.

Taking into account the symmetry of the structure and of the patterns of eddy currents, the model is reduced to the upper part of a half of a quadrant, as shown in Fig. 3. The quadrants are symmetric with respect to the XOZ-plane as well as the XOY-plane. The eddy currents are anti-symmetric with respect to the XOZ-plane and symmetric with respect to the XOY-plane.

The EDDYCUFF model of the TFCCS is shown in Fig. 3. The model is divided into four parts as shown in Fig. 4.

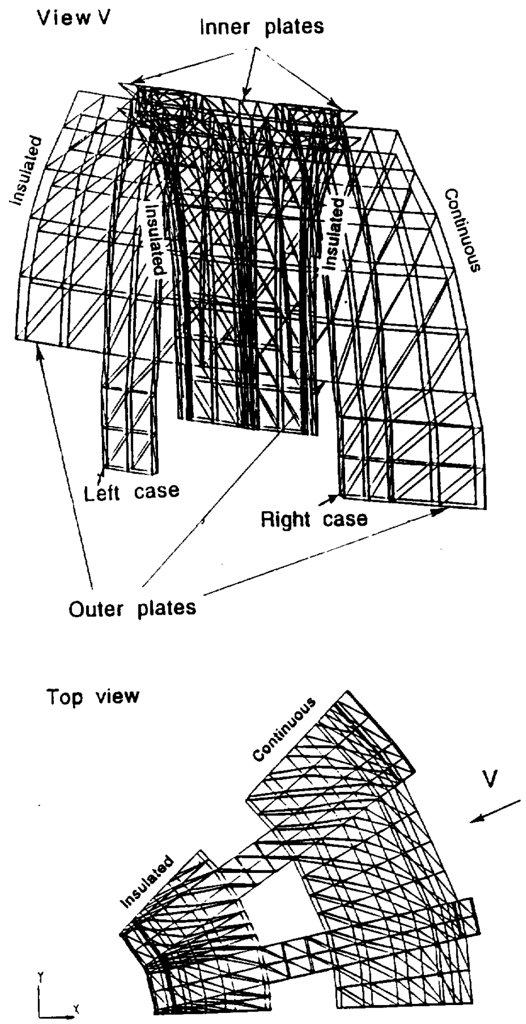

Fig. 3 The Finite Element Model

The four parts are:

- the left TF coil case which is located close to the bolted edge of the TF cold structure quadrant,
- the right TF coil case which is located close to the center of the TF cold structure quadrant,
- the inner plates belonging to the inner bore and lying between the two cases as well as between each of the cases and the corresponding insulated edge of the inner bore of the octant,
- the outer plates belonging to the outer part of the toroid and lying between the two cases as well as between the left case and the bolted edge and between the right case and the welded edge of the octant.

Joule losses are accumulated for each of these parts.

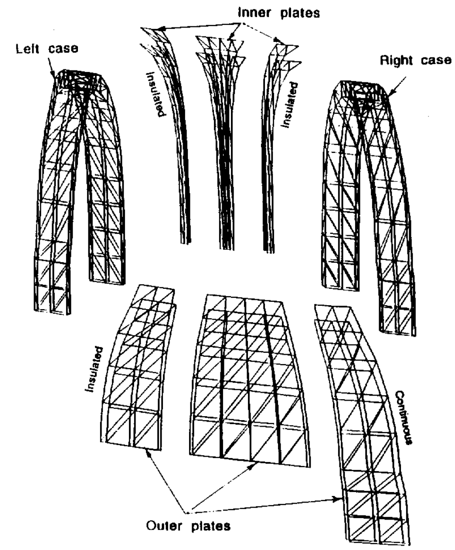

Fig. 4 Parts Diagram

The 14 PF coils and the plasma are modeled as solenoids. The time-dependent PF coil and the plasma currents are shown in Fig. 5. There is a 5 second ramp of the coil currens followed by the initiation blip. The plasma current is ramped from zero to 2 MA in 4 seconds. There is a transition from low β to high β at 9 seconds and back from high to low at 19 seconds. (β is the ratio of the plasma pressure over magnetic pressure. Higher β requires higher vertical field to equilibrate the plasma outward force. Going from low β to higher β the PF coil currents must increase, and vice versa.) There is a 9 second plasma current flattop. Finally, there is a 4 second plasma current ramp down.

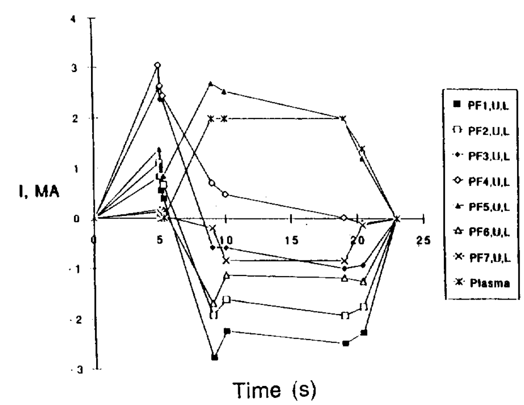

Fig. 5 Currents in the PF Coils

The magnetic fields due to the fast vertical position control (FVPC) coils shown in Fig. 1 are not taken into account in the analysis, since the eddy currents produced in the TFCCS by these coils are symmetric with respect to the geometric symmetry plane Z=0, whereas the eddy currents produced by the vertical stability control coils are anti-symmetric with respect to the same plane. Since these two systems of currents are orthogonal, their total Joule losses are equal to the sum of the Joule losses of the two systems of currents taken individually. The impact of these coils is presented in [4].

Figs. 6 and 7 present the power and the energy of Joule heating of the entire TF cold structure versus time. Fig. 5 shows that the maximum power of the Joule heating is about 50 kW. It occurs during a short plasma initiation blip in the vicinity of t=5 s, and during the transition from low β to high β (and vice versa). The total energy generated in the TF coil cold structure is about 0.31 MJ for this PF coil scenario.

The typical eddy current patterns in the cold structure are shown in Figs. 8 and 9. Fig. 10 gives a more detailed view if the eddy currents in the structural elements of the TFCCS. These figures illustrate the three dimensional nature of the eddy currents in the structure. The insulating breaks are evident, since the eddy currents are tangential to the edges. It means that the three dimensional eddy current analysis is essential for this problem.

Figs. 8 and 9 also show that at some moments of time the maximum eddy currents occur in the TF coil cases forming a closed path around the ports. It suggests a nonuniform distribution of heat dissipation and temperature in the TFCCS, which must be recooled to cryogenic temperatures between PF coil current pulses.

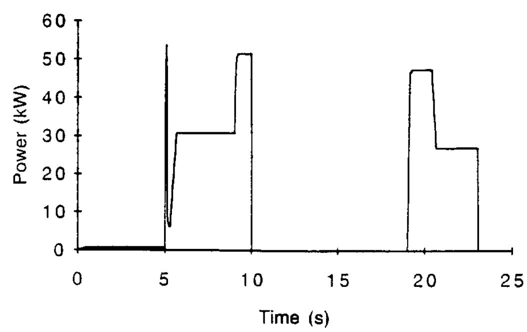

Fig. 6 Power Dissipation in the TFCCS

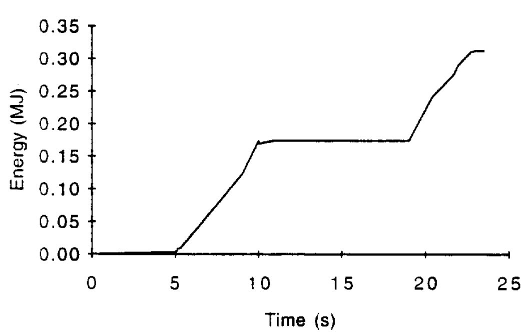

Fig. 7 Energy of Joule Heating of the TF Cold Structure

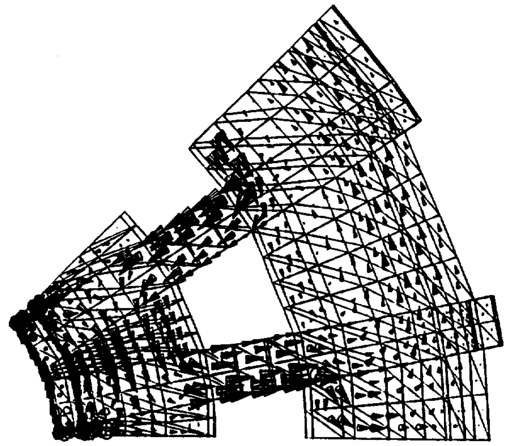

Fig. 8 Eddy Currents in the TFCCS

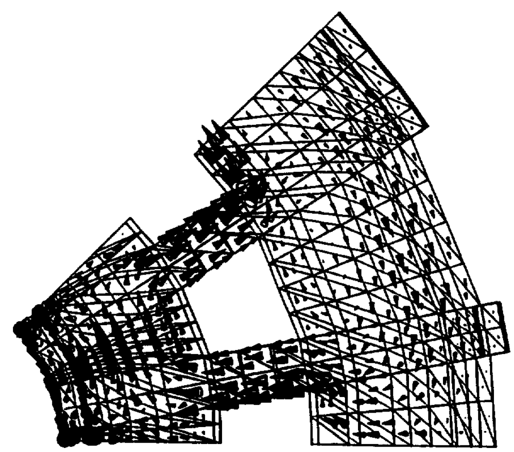

Fig. 9 Eddy Currents in the TFCS

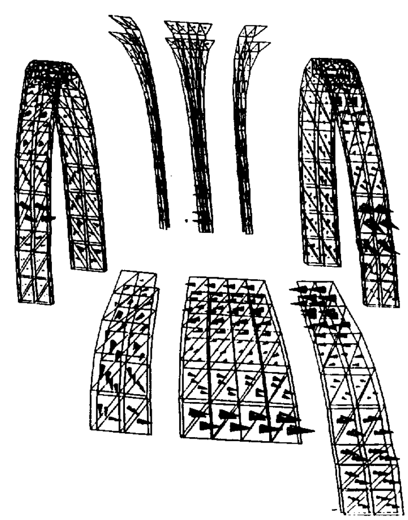

Fig. 10 Eddy Currents in the Structural Elements of the TFCCS

THERMAL TRANSIENT ANALYSIS

The 3-D, time-dependent eddy currents produce Joule losses in the TF coil cold structure. Although it is helpful, from a design perspective, to know the total amount of energy dissipated in the cold structure, detailed knowledge of the heat transfer paths and temperature distribution is critical to the successful operation of the magnet system. This information is required to design the superconductor and the cooling system (*e.g.*, size and location of cooling panels, flow rates, and refrigeration capacity). Local heating puts a thermal load on the conductor, which affects its stability and safety margin.

The analysis turns to ANSYS [5] to solve the thermal transient problem. The requirements are simple: a finite element model, material properties, time-dependent element-based heat loads, and thermal boundary conditions. The thermal analysis takes advantage of the EDDYCUFF model. A data transfer interface is written which generates files containing ANSYS node, element and real constant (shell thickness) commands. Element-based heat generation commands are also written for each time point. A single file is assembled with this data along with the appropriate solution and postprocessing commands.

The transient analysis is based on the ANSYS STIF57 3-D thermal shell element. For the purpose of demonstrating the modeling and solution procedure, constant material properties are assumed corresponding to the 4 K initial condition. In addition, heat transfer is limited to conduction within the TF coil case structure, leading to an adiabatic temperature rise. Later, more detailed analyses will include nonlinear properties, and heat transfer between the structure and coolant lines, panels, and the conductor winding pack.

Eddy current heat loads are defined for 87 time points. While all of the heating occurs within the first 23 seconds of the transient, the input is extended by one time point with no additional heating to determine the steady state metal temperature. This is a simple way of checking the analysis since the final temperature can also be determined by a hand calculation.

Fig. 11 shows the temperature contours in the TF coil support structure at the end of the PF coil current scenario (23 second into the transient). The plot indicates a maximum (MX) temperature of 15.7 K, occurring in the corner of the vertical port. This is consistent with the high eddy current patterns shown in Figs. 8 and 9.

In addition, the analysis indicates that after an artificially long soak time, the TF structure temperature is bounded between 5.6 K and 6.6 K. Assuming that this one degree gradient soaks in to a uniform 6.1 K, the temperature rise is 2.1 K. A hand calculation of the adiabatic temperature rise is simply equal to the total heat dissipated (0.31 MJ), divided by the mass of the structure (4644.3 kg) and the specific heat of the steel (1.99 J/kg K), or 2.1 K. This confirms that the material properties, mass and heat input are done properly, and lends credibility to the analysis.

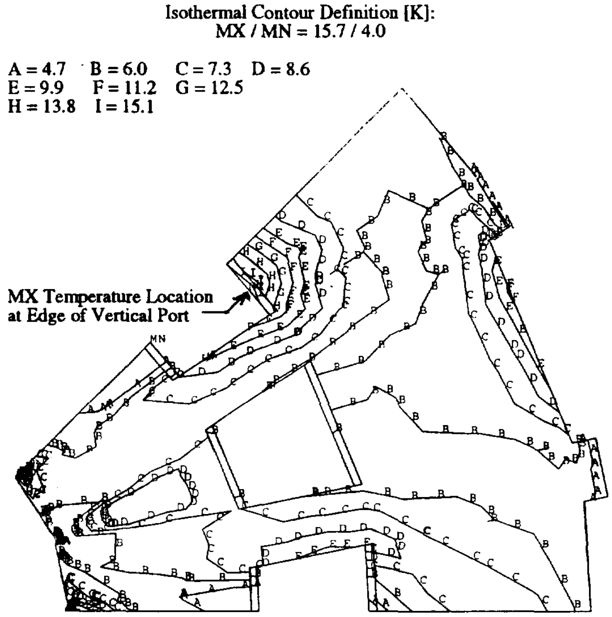

Fig. 11 Temperature Contours in TF Coil Case Structure at 23s

No transient finite element analysis is complete without a time stepping and mesh density optimization study. So the numerical thermal results presented here are preliminary. However, the objective of the analysis is satisfied, having developed an interface between EDDYCUFF and ANSYS, and successfully modeled a thermal transient produced by eddy currents in the TF coil case and support structure.

CONCLUSIONS

The total energy generated in the TF cold structure is about 0.31 MJ. The maximum power dissipated by Joule heating is about 50 kW. An interface has been created to transfer the EDDYCUFF model and time-dependent heating data into an ANSYS input file. A simple adiabatic thermal transient is performed, and the results seem reasonable.

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[5] ANSYS 5.0, Swanson Analysis Systems, Inc., Houston, PA.