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**THERMAL AND MECHANICAL ANALYSIS OF THE FARADAY SHIELD
FOR THE COMPACT IGNITION TOKAMAK**

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ABSTRACT

The antenna for the ion cyclotron resonance heating (ICRH) system of the Compact Ignition Tokamak (CIT) is protected from the plasma environment by a Faraday shield, an array of gas-cooled metallic tubes. The plasma side of the tubes is armored with graphite tiles, which can be either brazed or mechanically attached to the tube. The Faraday shield has been analyzed using finite element codes to model thermal and mechanical responses to typical CIT heating and disruption loads. Four representative materials (Inconel 718, tantalum-10 tungsten, copper alloy C17510, and molybdenum alloy T2M) and several combinations of tube and armor thicknesses were used in the thermal analysis, which revealed that maximum allowable temperatures were not exceeded for any of the four materials considered. The two-dimensional thermal stress analysis indicated Von Mises stresses greater than twice the yield stress for a tube constructed of Inconel 718 (the original design material) for the brazed-graphite design. Analysis of stresses caused by plasma disruption ($\vec{J} \times \vec{B}$) loads eliminated the copper and molybdenum alloys as candidate tube materials. Of the four materials considered, tantalum-10 tungsten performed the best for a brazed-graphite design, showing acceptable thermal stresses (69% of yield) and disruption stresses (42% of yield). A preliminary thermal analysis of the mechanically attached graphite scheme predicts minimal thermal stresses in the tube. The survivability of the graphite tubes in this scheme is yet to be analyzed.

1. INTRODUCTION

The mission of the Compact Ignition Tokamak (CIT) is to provide the necessary link between the transient deuterium-tritium (DT) operations scheduled for the Tokamak Fusion Test Reactor (TFTR) and the steady-state burn required of a future Engineering Test Reactor (ETR). Therefore, the CIT must be capable of forming and containing fully ignited DT plasmas for the purpose of studying alpha particle heating and its effect on plasma stability [1].

To achieve ignition of DT plasmas and to provide auxiliary heating of non-DT plasmas, CIT will employ an ion cyclotron resonance heating (ICRH) system. This system consists of six ports with two antennas per port; each antenna is capable of providing 1.6 MW to the plasma. The maximum power is available at a frequency of 95 MHz, but the radio frequency (rf) sources are tunable from 80 to 110 MHz. A detailed description of the operation of the ICRH antenna is given in the CIT Conceptual Design Report [1].

The ICRH launching structure, shown in Fig. 1.1, is protected from the harsh plasma environment by the Faraday shield tubes (at left in the figure). Figure 1.2 shows close-up views of the launcher and the staggered double row of Faraday shield tubes (the outermost row is covered on the plasma side by graphite armor).

The purpose of this study was to analyze the thermal and mechanical response of typical Faraday shield designs to the heat loads and mechanical loads incurred during a CIT pulse, including loads caused by plasma disruptions. A parametric study was conducted to determine the tube dimensions and materials for optimum thermal performance for a design in which the graphite armor is brazed to the tube. A brief study of a mechanical graphite attachment scheme analyzed the cool-down response over several ignition pulses. A two-dimensional thermal stress analysis was conducted for the brazed-graphite design. Because of time constraints, a detailed look at three-dimensional thermal stresses was not performed, although thermal stresses in the 90° elbow are expected to be crucial in determining the validity of a brazed-armor design.

Fig. 1.1. CIT ICRH antenna port.

Fig. 1.2. ICRH system design details.

2. ANALYSIS ASSUMPTIONS AND CONDITIONS

2.1 HEATING RATES FOR THERMAL MODEL

The Faraday shield tubes are subject to heating from three sources, each of which is represented in Fig. 2.1.

1. Radio frequency waves interact with the structure and cause a surface heat load. The nominal surface heat flux resulting from rf was taken to be 1.0 MW/m^2 , but several cases were run at 2.0 MW/m^2 , as indicated by the upper dotted line in the figure. The line at 1.57 MW/m^2 represents the best estimate, which was used in certain cases. For this model, the rf was

Fig. 2.1. Analysis assumptions—heat loads.

applied at time zero and continued at a constant level throughout the 5-s pulse.

2. Plasma particles impinging on the shield and plasma radiation lead to another surface heat load. If plasma growth takes place close to the ICRH antenna, the plasma heat flux will be higher prior to ignition than during the burn. Therefore, in the nominal case, the plasma surface heating ramps down from 1.0 MW/m^2 initially to 0.5 MW/m^2 at $t = 1.0 \text{ s}$, remains constant through $t = 5.0 \text{ s}$, and then drops to zero. Again, the dotted line represents an assumed "worst case" in which the plasma heating is initially 2.0 MW/m^2 .
3. During the ignited phase, fusion neutrons induce a volumetric heat load in the Faraday shield materials. The neutron wall loading used is 4.4 MW/m^2 applied from $t = 1.0 \text{ s}$ to $t = 5.0 \text{ s}$ and is zero at all other times.

2.2 DISRUPTION LOADS FOR MECHANICAL MODEL

In addition to the thermal stresses incurred because of the heat loads described in Sect. 2.1, the Faraday shield must be designed to withstand loads caused by plasma disruptions. Loads at various positions along the tube were obtained from a study by Bialek at Princeton Plasma Physics Laboratory (PPPL) for Inconel 718 [2]. These loads were scaled for the other materials by multiplying the Inconel loads by the ratio of the Inconel resistivity to the resistivity of the material in question. A more detailed discussion of the application of these disruption loads is provided in Appendix A.

2.3 MATERIAL CANDIDATES

Four materials were chosen to represent a range of material properties. Table 2.1 lists the four metals and several key properties for comparison. In all cases, graphite was used as the armor material. The thermal analysis considered both brazing and mechanical attachment schemes for affixing the graphite armor to the tube.

Table 2.1. Material properties

Material	Thermal conductivity (W/M·K)	Electrical resistivity ($\mu\Omega\cdot\text{cm}$)	Thermal expansion coefficient	Yield stress (MPa)	Maximum temperature (K)	Maximum ΔT (K) ^a	Nuclear heating (MW/m ²)
Inconel 718	15	120	11	655	900	490	31.0
Ta-10W	44	11	6	1010	1500	1107	85.5
Mo-TZM	117	4	5	700	1200	860	59.3
Cu-C17510	164	2	18	760	700	620	65.1
Graphite	290	--	4	--	--	--	35.0

^a Calculated from $\Delta T_{\text{max}} = \frac{2\delta_y}{ea}$.

2.4 THICKNESSES OF TUBE AND ARMOR

For the brazed armor attachment scheme, two tube wall thicknesses (2.0 and 3.175 mm) and three armor thicknesses (2, 5, and 10 mm) were employed, thus generating six data points for each material. In all cases, the inner diameter of the tube was 0.25 in. (6.35 mm).

For the mechanical armor attachment design and for the thermal stress and disruption load analyses, the pipe thickness was 3.175 mm (1/8 in.) and the graphite thickness was 5 mm, the values prescribed in the Conceptual Design Report [1].

2.5 COOLANT CONDITIONS

The presence of gaseous nitrogen coolant inside the tube is modeled by applying a convection boundary condition to the inner surface of the tube. A heat transfer coefficient of $1000 \text{ W/m}^2\cdot\text{K}$ was used, and the bulk coolant temperature was kept at 100 K throughout the tube.

3. ANALYSIS MODEL

3.1 CODES

Four different finite element codes were employed in this study: TACO2D, TOPAZ3D, NIKE2D, and NIKE3D.

TACO2D [3] is an implicit two-dimensional finite element heat transfer code, which may be used for linear and nonlinear problems, for either transient or steady-state analyses. The Faraday shield model involved a transient nonlinear analysis and took advantage of such features as heat flux, convection, and special internal boundary conditions, as well as internal heat generation.

TOPAZ3D [4] is based to some extent on the three-dimensional heat transfer code TACO3D, which is an extension of the TACO2D code. Most of the features available in TACO2D are included in TOPAZ3D, so the two- and three-dimensional thermal models were nearly identical with regard to thermal loadings, boundary conditions, and volumetric heating.

NIKE2D [5] is a two-dimensional implicit finite element code that calculates the finite deformation of solid elements. The two-dimensional thermal stress analysis model took advantage of the feature that allows NIKE2D to read in temperature states from a TACO2D plot file.

NIKE3D [6], an implicit three-dimensional finite element code, is capable of computing the finite deformations of solids, shells, and beams. A variety of material models are available, and either static or dynamic responses can be studied. The Faraday tube structural study looked at static responses and included such features as concentrated nodal loads and pressure boundary conditions.

3.2 MODEL

A typical mesh plot of the two-dimensional model used for the thermal analysis is shown in Fig. 3.1. The case shown modeled a 1/8-in.-thick pipe protected by 5 mm of graphite. The plasma heat flux is a sine function with its peak at the topmost node (angle = 90°), decreasing to zero at the bottom graphite nodes (angle = 0° and 180°).

$$\text{SURFACE HEAT FLUX AT ANY NODE ON GRAPHITE SURFACE} = \dot{q}_s = \dot{q}_p \sin \theta + \dot{q}_{RF} \cos \theta$$

Fig. 3.1. Analysis model—two-dimensional mesh plot.

On the other hand, the rf surface heat flux peaks where the high-frequency magnetic field is compressed most in passing between the shield tubes [7] (at the bottom edge of the graphite) and drops to zero at the top (a cosine function). Internal surface conditions were applied along the darkened segments to model either brazing (contact conductance = $10^6 \text{ W/m}^2\cdot\text{K}$) or mechanical attachment (radiative heat transfer only).

The three-dimensional model used for both the TOPAZ3D and the NIKE3D analysis is shown in Fig. 3.2, pictured here for 1/8-in.-thick pipe and 5 mm of graphite. Both the two- and three-dimensional thermal and structural models were generated by a preprocessor, which allows parametric studies of tube radii and thicknesses, graphite thicknesses, and surface heat loads, as well as longitudinal, radial, and circumferential variation of the number of nodes.

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Fig. 3.2. Analysis model—three-dimensional mesh plot.

4. RESULTS

4.1 TEMPERATURE RESPONSES

4.1.1 Brazed Attachment Scheme

Figures 4.1 through 4.4 show the temperature results for the four materials considered. In these graphs the maximum pipe temperature is plotted as a function of the graphite armor thickness for two pipe thicknesses (3.175 and 2.0 mm). Because this design relies on inertial cooling during the pulse (the nitrogen coolant is ineffective), lower

Fig. 4.1. $T_{\max}$ vs armor thickness for two pipe thicknesses—
Inconel 718.

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Fig. 4.2. $T_{\max}$ vs armor thickness for two pipe thicknesses—tantalum alloy Ta-10W.

peak temperatures are obtained for the larger pipe thickness (more heat is conducted to the back side of the shield). The inflection of the copper alloy curves for a pipe thickness of 3.175 mm is the result of a transient effect. A thick graphite armor results in a significant delay of the passage of surface heating through the structure. For the thinner graphite, the peak initial plasma heat flux passes through to the tube material before the volumetric heating (starting at $t = 1.0$ s) becomes dominant.

The curves in Figs. 4.1 through 4.4 were generated using a peak plasma heat flux of 1.0 MW/m^2 and an rf heat flux of 1.0 MW/m^2 . The isolated points above the curves demonstrate the increase in temperature

Fig. 4.3. $T_{\max}$ vs armor thickness for two pipe thicknesses—molybdenum alloy TZM.

that occurs when the peak plasma heat flux and the rf heat flux are both 2.0 MW/m^2 (the dotted line cases in Fig. 2.1). Based on these results, we conclude that peak temperatures at nominal conditions are not critically high for any of the materials studied. Figure 4.5 assembles in one graph the temperature responses for all four materials for a tube thickness of 3.175 mm.

Figures 4.6 through 4.9 show the temperature difference across two segments designated "A-B" and "A-C" and defined at the top of Fig. 4.6. Again, the curves represent the responses to nominal heat loads (1.0 MW/m^2), and the isolated data points correspond to the dotted

Fig. 4.4. $T_{\max}$ vs armor thickness for two pipe thicknesses—copper alloy C17510.

line cases of Fig. 2.1. Only Inconel 718 appears close to the limiting ΔT value, a limit which is useful mainly for comparison purposes. Figure 4.10 displays the maximum (A-C) ΔT for all four materials (3.175-mm tube thickness).

Figure 4.11 shows a typical time history plot (through 100 s) of nodal temperatures to demonstrate the cool-down performance. Although the cooling is ineffective during the pulse (through $t = 5.0$ s), the entire structure has been cooled to near the original temperature (100 K) in less than 100 s.

Fig. 4.5. $T_{\max}$ vs armor thickness for pipe thickness of 3.2 mm.

Fig. 4.6. Maximum ΔT vs armor thickness for two pipe thicknesses—
Inconel 718.

Fig. 4.7. Maximum ΔT vs armor thickness for two pipe thicknesses—tantalum alloy Ta-10W.

Fig. 4.8. Maximum ΔT vs armor thickness for two pipe thicknesses—molybdenum alloy TZM.

Fig. 4.9. Maximum ΔT vs armor thickness for two pipe thicknesses—copper alloy C17510.

Fig. 4.10. $\Delta T_{\max}$ vs armor thickness for pipe thickness of 3.2 mm.

Fig. 4.11. Temperature history for brazed-graphite design.

4.1.2 Mechanical Attachment Scheme

The mechanically attached graphite design was analyzed through five consecutive 1-h cycles for a 1/8-in.-thick Inconel 718 tube, and 5 mm of graphite armor. The rf heat flux used is 1.57 MW/m^2 ; the plasma heat flux is the 1.0 MW/m^2 case of Fig. 2.1. Figure 4.12 displays the nodal temperature response over the five cycles. The peak graphite temperature at the end of the first heating pulse is 924 K. Because the model assumed only radiative heat transfer between the graphite and the Inconel, the rate of cooling decreases rapidly as the graphite temperature drops. Thus, at the end of the first hour, the graphite temperature has decreased only to 350 K, leading to the thermal ratcheting effect observed. However, because of the rapid increase in the heat capacity of the graphite with increasing temperature (graphite $C_p = 2100 - 2292 \exp(-T/600) \text{ J/kg}\cdot\text{K}$) [8], the peak graphite temperature rises to only 970 K during the second pulse and remains essentially the same for each subsequent pulse.

Fig. 4.12. Temperature history for mechanically attached graphite.

4.2 STRESS RESPONSES

4.2.1 Disruption Loads

When applied to the three-dimensional structural model of the brazed design, disruption loads resulted in the stresses shown in Fig. 4.13 for the four materials. The deformations shown are scaled up by a factor of 10. Plasma disruption currents lead to a twisting movement such that the maximum primary stresses occur near the ends of the tube where it is attached to the supporting structure and coolant passages. Because of their relatively low resistivities, the copper alloy, C17510, and the molybdenum alloy, TZM, incur excessive stresses. The stresses on the tantalum-10 tungsten and Inconel 718 are acceptable.

The stresses caused by disruption loads are essentially the same for the mechanically attached graphite design as for the brazed

Fig. 4.13. Stresses caused by disruption loads.

design. The graphite armor does not influence the development of disruption-induced stresses.

4.2.2 Thermal Stress

Temperature states for the brazed design found by a TACO2D analysis were used as input to the NIKE2D model. One change from the previous TACO2D model was made: the average rf surface heat load was set to 1.0 MW/m^2 (by setting the peak value to 1.57 MW/m^2). The four materials were analyzed to determine the resulting thermal stresses for nominal tube dimensions. Figure 4.14 shows the time history of the maximum Von Mises stress through the pulse for the four materials studied, with the

Fig. 4.14. Maximum thermal Von Mises stress vs time (two-dimensional analysis).

thermal stress limits ($2 \cdot \text{yield stress}, \sigma_y$) of the materials. Table 2.1 shows that Inconel 718 and C17510 differ greatly from graphite in regard to their thermal expansion coefficients, and this difference is illustrated by the high thermal stresses in these two materials. In contrast, TZM and tantalum-10 tungsten are more closely matched to graphite for thermal expansion, and this accounts for the lower thermal stresses observed in these materials.

Table 4.1 summarizes the stress results for the thermal and disruption stress analyses. The peak thermal stresses may be compared to the value of $2\sigma_y$, the design criterion for secondary stress, which indicates that Inconel 718 incurs excessive stresses. For the disruption loads, if the criterion that the Von Mises stress should not exceed the

Table 4.1. Stress summary for the brazed design

Material	Peak thermal Von Mises stress (MPa)	$2\sigma_y$	Peak disruption Von Mises stress (MPa)	$\frac{2}{3} \sigma_y$ (MPa)
Inconel 718	1600	1310	39	437
Ta-10W	697	2020	426	673
Mo-TZM	756	1400	1083	467
Cu-C17510	1030	1516	1841	505

allowable primary stress ($2/3\sigma_y$) is applied, the copper alloy C17510 and the molybdenum alloy TZM clearly fail.

No NIKE2D analysis of the thermal stress for the mechanically attached graphite design was performed. However, the thermal analysis revealed that the temperature effects in the tube material are insignificant (maximum temperature = 143 K), leading to essentially zero thermal stress. Because the graphite armor is not intimately attached to the coolant tube, the difference in thermal expansion between the two materials is not a dominant factor as it appears to be for the brazed design. It is still possible, however, that a change in curvature of the graphite tiles will lead to significant stresses, an effect that will be considered in future work.

5. CONCLUSIONS

5.1 BRAZED-GRAPHITE DESIGN

The two-dimensional thermal analysis of the Faraday shield design with graphite brazed to Inconel 718, tantalum alloy, copper alloy, or molybdenum alloy tubes showed that maximum allowable temperatures were not exceeded for the range of surface heat fluxes described in Sect. 2. However, for the "worst case" heat flux values, the structural properties of copper alloy C17510 decreased significantly.

Thermal stresses evaluated by the two-dimensional analysis were found to be excessive for Inconel ($2.4 \cdot \sigma_y$) and acceptable for the other three materials. Yet to be studied, however, are the three-dimensional thermal stresses, which could be critical for the brazed-graphite design.

The disruption load analysis eliminated copper alloy 17510 and molybdenum alloy TZM as candidate materials, while Inconel 718 and tantalum-10 tungsten incurred acceptable stresses.

Because tantalum-10 has the largest margin of safety with regard to both thermal and disruption stresses, this alloy or a material with similar properties is recommended if the brazed-graphite design is pursued.

5.2 MECHANICALLY ATTACHED GRAPHITE DESIGN

The thermal analysis revealed no temperature-related problems for a design in which the graphite tiles are mechanically attached to the coolant tube. Essentially no thermal ratcheting was observed in the graphite, and the temperature rise in the coolant tube material was insignificant ($T_{\max} = 143$ K for Inconel 718).

The thermal analysis indicated that thermal stresses are not a critical factor in determining the tube material. Any one of the four materials considered in this report is acceptable from a thermal stress standpoint.

The conclusions of the disruption load analysis for the brazed design also apply to the mechanically attached graphite design:

Cu-C17510 and Mo-TZM suffer unacceptable stresses caused by disruption currents.

Therefore, for a mechanical attachment scheme, Inconel 718 and tantalum-10 tungsten have been shown to be acceptable materials. More conventional materials such as 304 stainless steel may also be acceptable for this design.

5.3 FUTURE WORK

Thermal stresses in three dimensions are expected to be a critical factor for the brazed-graphite armor design. Because both ends of the Faraday tube are fixed, thermal expansion must result in a bowing of the tube. The change in curvature of the pipe (especially through the 90° elbow) needs to be analyzed to determine its effect on the graphite tiles. Also, the model should treat the braze as an actual material, rather than employing a contact conductance as was used in the two-dimensional model. This will provide a more accurate representation of the tube/graphite boundary.

A closer examination should be made of the temperature-related stresses in the mechanically attached graphite design. This study should include modeling of the particular attachment device, such as a welded stud, to determine the stresses caused by thermal expansion of the graphite.

Appendix A

APPLICATION OF DISRUPTION LOADS TO THREE-DIMENSIONAL STRUCTURAL MODEL

Disruption loads at various points along the Faraday shield tube were obtained from a study by Bialek at PPPL [2]. The disruption model used in this study assumed a stationary plasma disruption, a circular plasma, and a current decay rate of 1 MA/ms. The antenna material used was Inconel 718, and the Faraday shield model lumped tubes together in groups of four. The resulting loads were divided by four for application to the NIKE3D structural model described in this report. Loads to be applied in the NIKE3D model were interpolated from the Bialek values, shown in Fig. A.1

Because the plasma disruption current was assumed to vary inversely with the resistivity of the Faraday shield material, the disruption

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Fig. A.1. Disruption forces (Inconel model).

forces (given by $\vec{J} \times \vec{B}$) were also scaled by resistivity. Thus, the disruption force in TZM at a given point was obtained by multiplying the force at the corresponding point in the Inconel model times the factor ρ_I/ρ_T , where ρ_I and ρ_T are the resistivities ($\mu\Omega\cdot\text{cm}$) of Inconel and TZM, respectively. The load factors used are:

<u>Material X</u>	<u>Resistivity factor ρ_I/ρ_X</u>
Inconel	1.0
Ta-10W	10.7
TZM	27.3
C17510	50.0

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