STRESS ANALYSIS OF A DOUBLE-WALL VACUUM VESSEL FOR ITER*

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ABSTRACT

The preliminary structural analyses performed in support of the design of the vacuum vessel for the International Thermonuclear Experimental Reactor (ITER) are described. A thin, double-wall, all-welded structure is the proposed design concept analyzed. The results of the static stress analysis indicate the adequacy of such a structure. The effects of the proposed high-aspect-ratio design configuration on loading and stresses are also discussed.

INTRODUCTION

The vacuum vessel for the International Thermonuclear Experimental Reactor (ITER) is subject to high mechanical stresses induced by substantial loads on the vessel walls.¹ The greatest of these loads are electromagnetic forces produced during plasma disruption. Other loads, namely thermal gradients and internal pressure, are significant but produce a lesser degree of stress in the vessel. The proposed thin-wall "sandwich" structure has been developed and modeled for finite element analysis. MC/NASTRAN² was chosen as the analysis code for the stress calculations. Models were created for both the reference ITER and high-aspect-ratio design (HARD) configurations. The purpose of the analysis was to study the stress in the vessel as the disruption progressed and prove the feasibility of the thin wall concept as a reliable structure for ITER. Electromagnetic forces were produced by the EDDYCUFF code³ and mapped to the structural model. Stress versus time studies were done for a single-filament, reference fast vertical disruption and for a refined multifilament disruption model.

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FINITE ELEMENT MODELS

Three finite element models were created for analysis:

1. coarse ITER geometry
2. refined ITER geometry
3. HARD Geometry.

Each finite element model was a one-sixteenth toroidal segment of the vacuum vessel geometry. The segment is cut vertically through the center of the radial port. This corresponds to the proposed segmentation scheme for assembly of ITER. The one-sixteenth segment was analyzed by the cyclic symmetry module of NASTRAN. Therefore, the model was numerically rotated through 360° to complete the torus. The double wall of the vessel is modeled by inner and outer face sheets, separated by poloidal "ribs." The first model had a relatively coarse mesh and allowed for only five ribs angularly spaced through the segment. Vertical stiffening beams were added to the outboard side of the model after initial analysis suggested that greater support was required. The vertical and radial port walls were given stiffness parameters equivalent to those of a "sandwich" section representing the actual design. The geometry of the model was symmetric about the midline of the machine and none of the bulkheads, port extensions, or vacuum ducts were included, since these components were a significant distance from any electromagnetic loading. The original model was used to compare the stress distribution for different disruption models, time steps, and geometric parameters. The first model was loaded with nodal forces. Later on in the process, EDDYCUFF was modified to produce element pressures, thus providing a more realistic model of magnetic fields for the analysis. The second model employed was the same ITER geometry with a greatly refined mesh (Fig. 1). The fine mesh allowed for decreased poloidal rib spacing as well as greater accuracy in the results. The added poloidal ribs reduced local bending of the face sheets. This forced the walls to behave like a solid section. The third model created was the proposed HARD geometry. The reference ITER vacuum vessel and the HARD

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vessel are compared in Fig. 2. The HARD model was given exactly the same properties and approximately the same mesh configuration as the refined ITER model. Therefore, a valid comparison of the two designs could be accomplished.

Fig. 1. ITER CDA Finite Element Model

Fig. 2. HARD/ITER CDA Comparison

LOADS

Various load sets were applied to the models during the analysis.

1. Pressure - 2 Atm (200,000 Pa)
2. Thermal - Joule Heating *
3. Electromagnetic - Reference Disruption *

TSC Case 0705B *

* Calculated by EDDYCUFF

Pressure on the vacuum vessel was an independently applied load. A 2-atm pressure load was applied to the inner faces of the ITER model to determine its pressure safety.

Temperature gradients were also applied to the model. EDDYCUFF calculated the Joule heating of the walls for the duration of a plasma disruption. A specific fraction of the total temperature increase was applied to the model for each time step studied. The fraction corresponded to the percentage of the total power dissipated in the vessel up to that time integrated from the vessel current versus time plot.

Electromagnetic (EM) loads⁴ were the principal concern of the analysis. The EM loads were first calculated for the reference fast vertical disruption. The vacuum vessel current for the reference disruption simulation peaks at the end of the plasma decay, or 22 ms. This information was used to produce a starting point for the analysis by presuming this to be the "worst-case" loading. Several other load cases, ranging from 2 to 34 ms, were analyzed. Next, loads were calculated from a multifilament plasma disruption model developed using data generated by the Tokamak Simulation Code (TSC). TSC produces time-varying fields that provide a driver to EDDYCUFF's three-dimensional conducting model. The current quench of this plasma began at approximately 570 ms into its motion, with the vacuum vessel current peaking at around 600 ms (Fig. 3). Again, several load cases were applied to the structural model of the ITER vessel. The major portion of the force on the vessel is in the radial direction (Fig. 4). The radial force reaches a magnitude of approximately 40 MN per radian. The net vertical force peaks at only 4 MN per radian. The outboard side of the vacuum vessel with its integral passive stability plates carries a majority of the current density produced by a disruption. It follows that the outboard side is also the most heavily loaded section of the vessel. The poloidal distribution of the loads for the HARD configuration is somewhat different from that in the baseline ITER due to the change in geometry. The magnitudes of the forces produced by the HARD model disruption simulation are less than those of ITER. Figure 5 shows that for the same plasma decay time (20 ms assumed for the analysis) the net radial force is reduced

from -42 MN/rad to -21 MN/rad. This reduction in force is the effect of 30% less current in the HARD configuration.

Fig. 3. Stress and Current vs. Time

Fig. 4. Net Force vs. Time

Fig. 5. Net Radial Force Comparison

RESULTS

The ITER model was first analyzed with the 22-ms reference disruption load case. The maximum Von Mises stress was calculated to be 372 MPa. The results of the stress analysis reflected the heavy outboard loading by finding the maximum stresses around the radial ports. The initial attempt to reduce the stress was to add vertical stiffening beams to the structure. The added stiffness significantly changed the deflection of the structure and decreased the maximum Von Mises stress to 300 MPa. Stress results at 2, 6, 10, 14, 18, 22, 26, 30, and 34 ms were calculated to study the stress versus time behavior of the vacuum vessel during disruption. The results were as expected, with the stress peaking simultaneously with the vessel current. The stress results from the thermal load case (85 MPa) and the pressure load case (135 MPa) were small compared to the EM stress results. A fraction of the thermal results was superimposed on the EM results, as discussed previously. This produced an insignificant change in the overall stress in the vessel. Next, the electromagnetic loads from the multifilament simulation were applied to the model. Load cases at times from 560 to 600 ms in 10-ms increments were analyzed. Again, the maximum stress was closely coupled to the vessel current and peaked at 275 MPa (Fig. 3).

The refined ITER model was loaded with electromagnetic pressures at the 606-ms point in the plasma disruption. This was the moment of greatest net force on the vacuum vessel as calculated by EDDYCUFF (Fig. 4). The results from the analysis showed a decrease in the maximum Von Mises stress (257 MPa) from that in the original model.

Deformation of the vessel segment is illustrated in Fig. 6. Examination of the normal stresses revealed large compressive stresses in the toroidal direction. The additional poloidal ribs, being perpendicular to the direction of this normal stress, produced little relief and therefore did not have as much effect on the stress as expected. From this analysis, it was determined that, in general, neither rib spacing or rib thickness had a major effect on the results. The coolant pressure inside the walls would be the critical load when determining the rib spacing. The thickness of the face sheets was found to be more critical to the finite element results. The face sheet thickness is somewhat limited, however, by the required $20\text{-}\mu\Omega$ resistance of the vacuum vessel. The elements being stressed above 200 MPa were small localized areas around the lower corners of the radial ports. Adding 1 cm to the inner face sheet thickness in these areas reduced the maximum Von Mises stress to 226 MPa. Stresses in this range would allow a safety factor on the 275-MPa yield strength of 316 stainless steel. The analysis of the HARD model produced a maximum Von Mises stress of 156 MPa. This stress compares with the 254-MPa stress in the ITER configuration. The reduced plasma current is primarily responsible for the lower stresses in HARD. Table 1 presents stress analysis results, comparing the effect of major variables on the results. The significant variables are plasma current, EDDYCUFF driver, model geometry, and decay rate.

Fig. 6. Deformed Shape

TABLE 1
Stress Analysis Results

LOAD CASE	PLASMA CURRENT	DRIVER FILAMENTS	MODEL GEOMETRY	DECAY RATE	MAX STRESS
A	28 MA	SINGLE	5 RIB ITER CDA	1.3 MA/ms	444 MPA
D	22 MA	SINGLE	5 RIB ITER CDA	1.0 MA/ms	270 MPA
C	22 MA	MULTI	5 RIB ITER CDA	0.6 MA/ms	275 MPA
U	22 MA	MULTI	15 RIB ITER CDA	0.6 MA/ms	257 MPA
E	14.9 MA	MULTI	17 RIB HARD	0.4 MA/ms	156 MPA

CONCLUSION

The results of the vacuum vessel stress analysis proved that the thin-wall "sandwich" structure is a feasible alternative to the ITER baseline thick-wall design. The vacuum vessel could be easily cooled and operate with a reasonable factor of safety during a plasma disruption. Further development and design could easily eliminate any problem areas or stress concentrations remaining in the vacuum vessel design. The analysis of the HARD configuration revealed some changes in load distribution and magnitude, reflected in lower stresses than in the ITER CDA design.

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