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THERMAL ANALYSIS TO CALCULATE THE VESSEL TEMPERATURE AND STRESS IN ALCATOR C-MOD DUE TO THE DIVERTOR UPGRADE *

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Alcator C-Mod is planning an upgrade to its outer divertor. The upgrade is intended to correct the existing outer divertor alignment with the plasma, and to operate at elevated temperatures. Higher temperature operation will allow study of edge physics behavior at reactor relevant temperatures. The outer divertor and tiles will be capable of operating at 600°C. Longer pulse length, together with the plasma and RF heat of 9MW, and the inclusion of heater elements within the outer divertor produces radiative energy which makes the sustained operation much more difficult than before. An ANSYS model based on ref. 1 was built for the global thermal analysis of C-Mod. It models the radiative surfaces inside the vessel and between the components, and also includes plasma energy deposition. Different geometries have been simulated and compared. Results show that steady state operation with the divertor at 600°C is possible with no damage to major vessel internal components. The differential temperature between inner divertor structure, or "girdle" and inner vessel wall is ~70°C. This differential temperature is limited by the capacity of the studs that hold the inner divertor backing plates to the vessel wall. At a 70°C temperature differential the stress on the studs is within allowable limits. The thermal model was then used for a stress pass to quantify vessel shell stresses where thermal gradients are significant.

I. INTRODUCTION

Alcator C-Mod is proposed to operate with its outer divertor and tiles operating at 600°C.[2] C-Mod is cooled by a liquid nitrogen drip system which is intended to begin a plasma pulse with the coils at liquid nitrogen temperature. Heaters are used to maintain the vessel at room temperature. The new system will selectively turn off the heaters and includes heater elements in the outer divertor. Together with the plasma and RF heat of 9MW, radiation energy produced by plasma and high temperature outer divertor makes the sustained operation much more difficult than before. While the outer divertor is at an elevated temperature, the rest of the components, including vessel and especially some parts not well connected to any heat sink, have to limit their temperature rise or be able to survive the higher thermal stress.[3] A map of the radiative power around the interior of the vessel was developed to guide upgrade of vessel internals to survive the increases in energy coming from longer pulses, higher RF power, and the high temperature outer divertor. A modeling of the proposed outer divertor heaters is included. Their performance is compared with results from heat transfer analyses of detailed local models of the divertor and heater array.[4]

II. MODEL DESCRIPTION

An ANSYS model based on ref. 1 was built for the global thermal analysis of C-Mod (Fig. 1). It includes an improved modeling of radiative and convective energy transfer, and updated details of the outer divertor design.

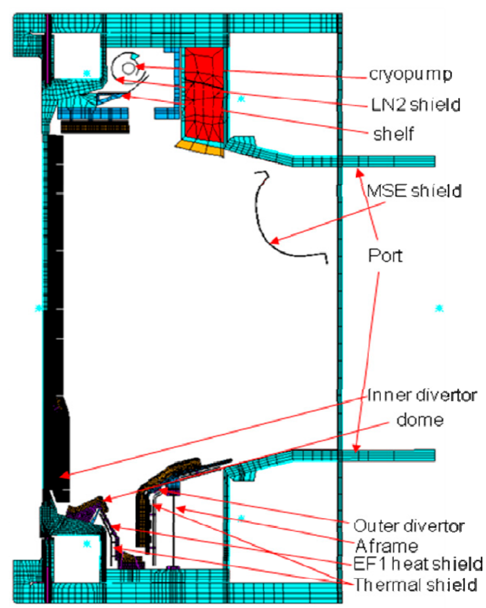

Fig. 1. 2D axisymmetric thermal model of C-Mod: Discrete components are modeled to be 360 degree continuous with equivalent thermal conductivity.

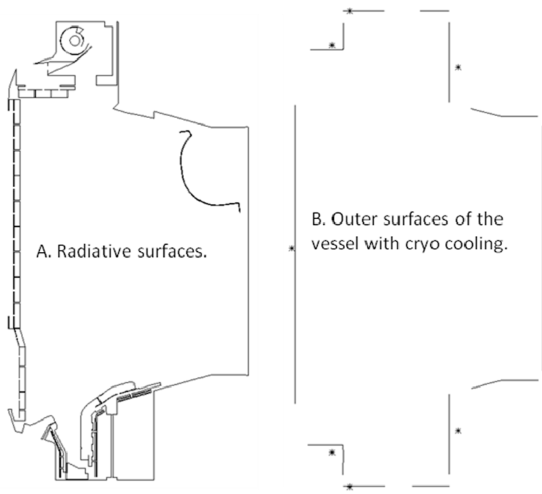

Fig. 2. A) Radiative surfaces inside the vessel. B) Outer surfaces of the vessel with cryo-cooling.

It models the radiative surfaces inside the vessel and between the components (Fig. 2A). View factors are calculated by /AUX12. For verification, two small areas were selected to calculate the view factor manually and the result is consistent with /AUX12. The vessel wall is surrounded with cryo-cooling tubes or nitrogen gas but it is hard to know the cooling power. To maintain wall temperature at room temperature, C-Mod has many heaters and thermal couples wrapping around the vessel walls to provide heat when necessary. The average power of these heaters was monitored and recorded. With the upgraded C-Mod, the plasma will have higher stored energy and the hot outer divertor will radiate more heat to the vessel wall, which will replace a portion of the heaters' heat. Thus, in this thermal analysis, convection cooling is added to the outside surface of vessel (Fig. 2B) and the film coefficients are calculated based on the operational heater data. The model is 2D axisymmetric. The discrete components are modeled to be 360 degree continuous with equivalent material properties. Plasma energy of typical scenarios is applied to the vessel and divertors. Different geometries have been simulated and compared. Heat loads on vessel inner and outer walls, EF and EF1 pockets and thermal shields were read out for comparison with existing data. Then, the model was used to calculate stresses based on the thermal results.
This paper covers the work during past two years. Meanwhile the design of some components was changed. Typical scenarios and operating conditions were discussed and modified. Thus in the following sessions, the model may be slightly different than the currently proposed outer divertor details.

III. Steady state analysis with outer divertor at 600°C

The first case of interest is a steady state run with outer divertor at 600°C and no plasma energy deposition. This case shows how radiation is distributed throughout the vessel, especially the lower half, and what thermal stresses arise in the vessel and divertor components.

III.A. Temperature distribution

Fig. 3 shows the temperature of outer divertor. This is the worst case simulation with high emissivity (0.4). To heat it to 600°C requires 23.1 KW of divertor heater power and takes about 3 hours. About 238 W will deposit on the cryo-cooler and the rest to the vessel. A multi-layer thermal shield at the EF1 pocket directly faces the outer divertor and its shield temperature can reach 389°C (Fig. 4). Although the vessel wall is protected by tiles and thermal shields, it is still heated by conduction and radiation, especially the lower half of inner wall behind the inner divertor. Due to the cryo-cooling, the temperature of vessel wall can be kept within about 100°C (Fig. 5). Currently in this model, only 8 thermostat points are set to control the vessel wall temperature. This is another reason for the temperature variance and thermal stress, which will be improved later.

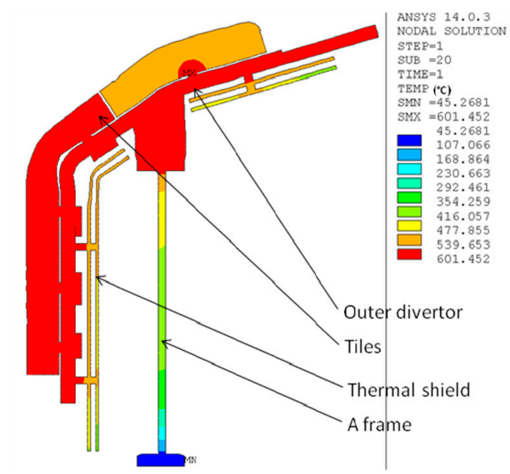

Fig. 3. Temperature of outer divertor.

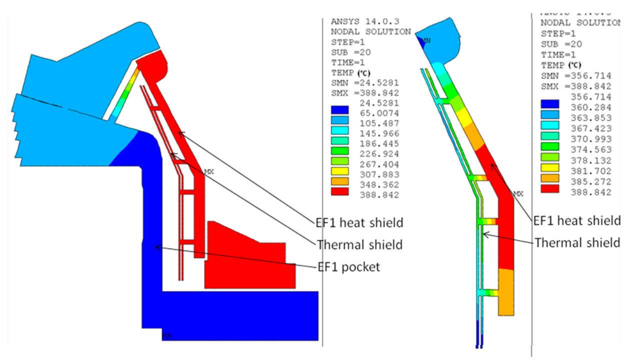

Fig. 4. Temperature of EF1 pocket and thermal shields.

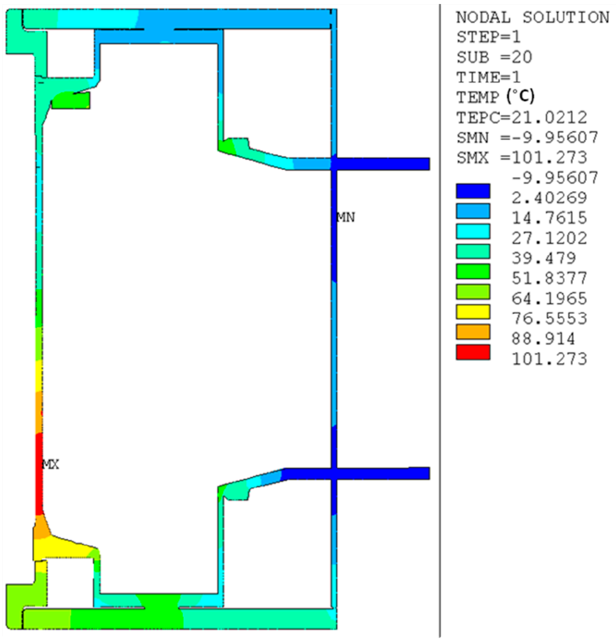

Fig. 5. Vessel wall temperature distribution.

III.B. Vessel thermal stress.

Due to the temperature control via heaters on the vessel wall, thermal stresses of most of the areas are very low, except for the EF1 pocket. The top of the EF1 pocket has a relatively higher temperature than the vessel floor, which produces a high stress, 333 MPa, at the corner (Fig. 6). This stress can be reduced by either providing more cooling to the EF1 pocket to lower the temperature of the top, or heating the vessel floor slightly to reduce the temperature difference. In Fig. 7, the thermal stress at the corner was reduced to 233 MPa by heating the floor.

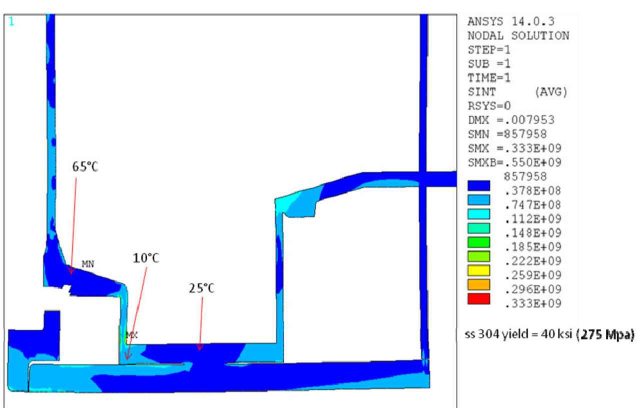

Fig. 6. Thermal stress (Pa) of EF1 pocket. (focus more on area of interest, zoom in on EF1 pocket.)

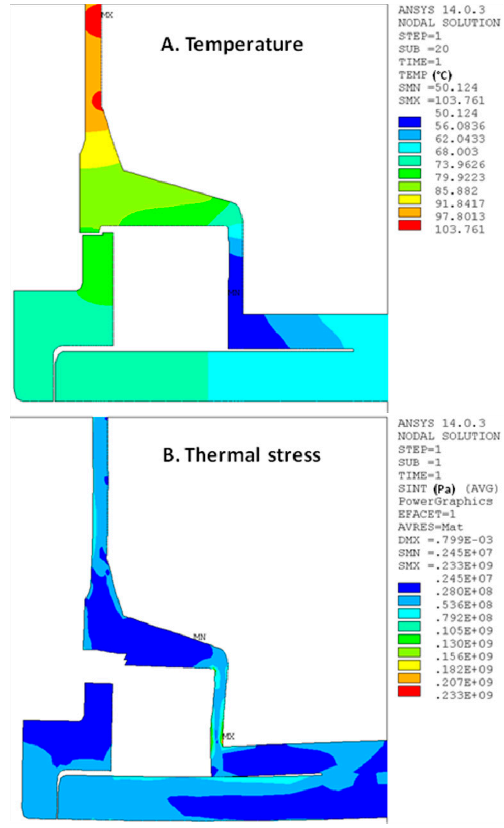

Fig. 7. By slightly heating the floor (A), the EF1 pocket corner stress was reduced (B).

IV. Transient analysis based on 2 typical operation scenarios.

Due to the space limit of this paper, 2 typical scenarios are presented here to show the simulated transient behavior of C-mod with the new heated outer divertor. The first scenario assumes 8MW of plasma power, a long pulse of 4 seconds, and 1200 seconds of cooling between pulses (24 shots/day). The second scenario assumes 8MW of plasma power, a pulse length of 3 seconds, a 600°C outer divertor, and 1200 seconds of cooling between pulses (24 shots/day). It is hard to know the exact emissivity value of radiative surfaces in the vessel. While boron vapor deposition may increase the emissivity and scheduled maintenance will reduce it. Thus we estimate the emissivity to be between 0.4 and 0.2 and compare the results. Fig. 8 lists the temperature evaluation points. From previous analysis, to reduce the stress in the studs that fix inner divertor to the wall, the temperature difference (wall_t1-wall_t2) should be less than 100°C. (This analysis was completed two years ago and the model was a little different from current one.)

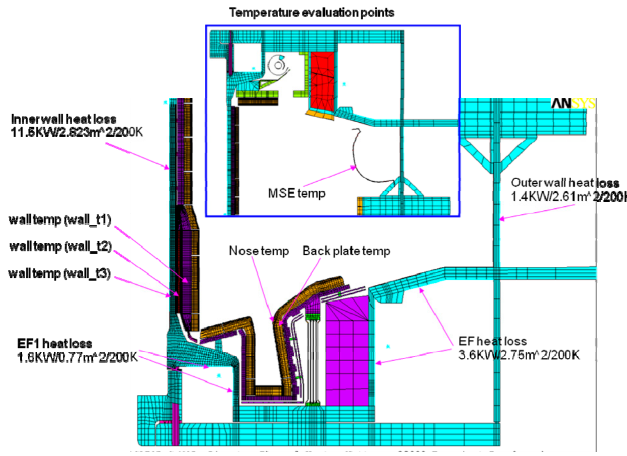

Fig. 8. Temperature evaluation points.

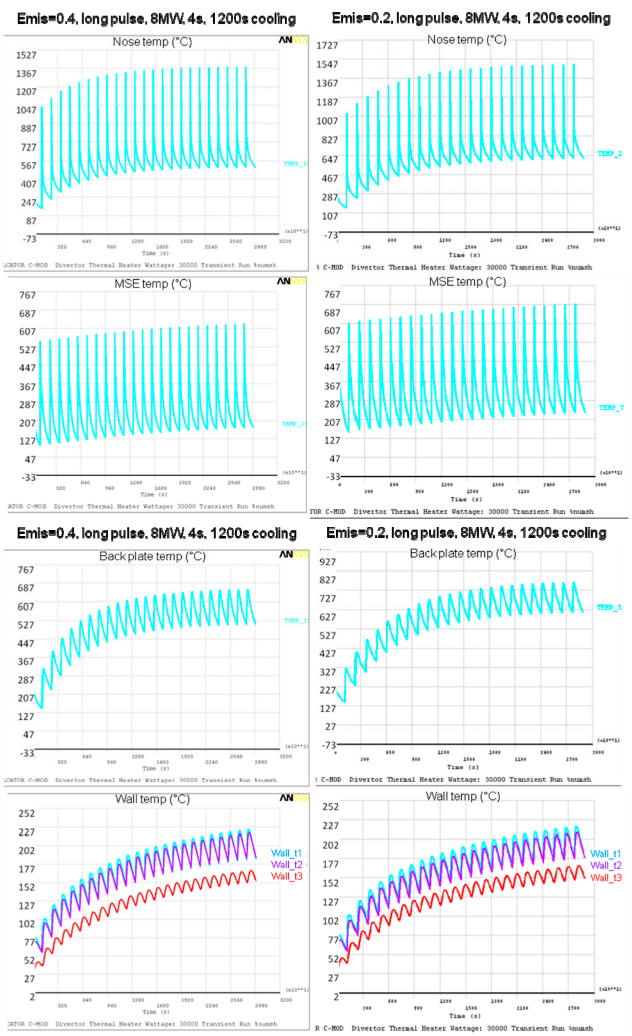

Fig. 9. 8MW plasma energy, long pulse 4 seconds, 1200 seconds cooling between pulses (24 shots/day).

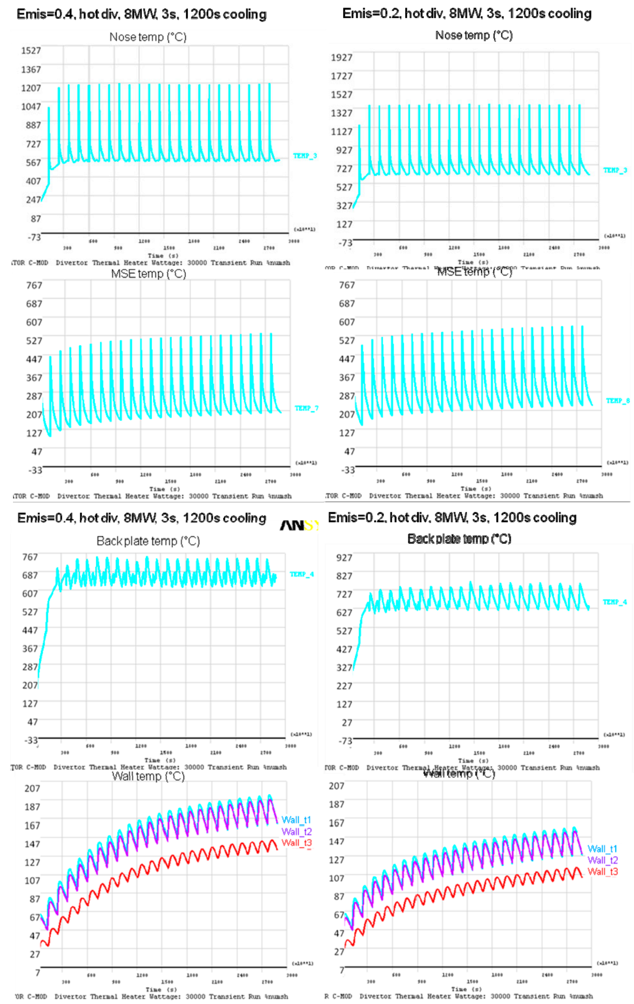

Fig. 10. 8MW plasma power, long pulse 3 seconds, heaterd outer divertor, 1200 seconds cooling between pulses (24 shots/day).

In fig. 9, outer divertor nose temperature is 1367°C when emis=0.4 and 1507°C when emis=0.2, at the end of a day. In fig. 10, nose temperature is lower to 1207°C when emis=0.4 and 1340°C when emis=0.2, which is similar to MSE temperature. For all these plasma facing components, their temperature mainly depends on the plasma heating and radiation. With higher radiation rate, the energy soon re-distributes in the system and is extracted from the vessel wall. In fig. 9, the back plate temperature is 660°C when emis=0.4 and 777°C when emis=0.2, at the end of a day. In fig. 10, back plate is heated, and within 30 minutes, its temperature reaches 600°C and then be kept within 600~777°C. In both cases, vessel wall and inner divertor temperatures are kept below 225°C and temperature difference less than 70°C. To keep the vessel thermal stress low, vessel wall temperature should be within 100°C. Thus the machine will not be operated at full power all day long. For case one, it can run five shots and case two, nine shots. Like this, all these temperatures are within allowable. With outer divertor heated to 600~777°C, it will expand 6~7 mm in radial direction and about 1 mm vertically.[5] The design of A frame with spherical bearing to support outer divertor can tolerate this thermal expansion without adding thermal stress to it.[6]

V. CONCLUSIONS

Results show that the differential temperature between inner divertor "girdle" structure and inner vessel wall is ~70°C so that the stress on the studs will be within allowable stress levels. Heat loads on vessel inner and outer walls, EF and EF1 pockets and thermal shields are read out and comparable to existing data. Then the model was used to calculate stresses based on these thermal results. Initially, the peak stress of 333 MPa occurred at the EF1 pocket, which exceeds the allowable stress. This stress was reduced by making the EF1 pocket and floor temperatures more uniform, by either providing more cooling to the EF1 pocket to lower the temperature of its top, or heating the vessel floor slightly to reduce the temperature difference between the two areas. A run with heating of the vessel floor shows that this stress can be reduced to 233 MPa. Transient analysis with 8 MW of plasma power, for both long pulse and hot divertor scenarios, shows that the vessel and component temperatures are within allowable values. When combined with plasma energy deposition, the outer divertor can be heated to 600°C within thirty minutes. Hot divertor will expand 6~7 mm radially and 1 mm vertically,[5] which will be tolerated by the A frame supports.[6]

This model was also used to simulate a variety of scenarios, including faulted operational conditions, like loss of cryo-cooling and loss of vacuum pressure resulting from a window breaking.

ACKNOWLEDGMENTS

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