**FRACTURE AND CREEP IN AN ALL-TUNGSTEN DIVERTOR FOR ARIES**

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*The ARIES project is currently proposing an all-tungsten divertor for their tokamak designs. In designing such a component, fracture will be a critical failure mechanism, due to the limited ductility of the tungsten. Hence, this paper presents a series of fracture mechanics-based analyses to demonstrate the feasibility of using an all-tungsten divertor in a commercial device. The analyses presented here employ a commercial finite element code (ANSYS) to carry out three-dimensional thermal, mechanical, and fracture calculations. Due to the inelastic deformations produced by the high temperatures and stresses in the component, the fracture calculations employ the J-Integral, a path-independent contour integral that estimates the strain energy release rate for a crack of assumed geometry. Elliptical surface cracks are introduced both inside and outside the coolant channel and steady state calculations are carried out for both full power and cold shutdown conditions. It is determined that the critical crack is on the inside of the coolant channel and the largest forcing is during full power. In addition, transient calculations are carried out to simulate edge localized modes (ELMs) in the plasma and conclusions are drawn with respect to the severity of these events and their effect on the lifetime of the component. Finally, thermal creep is considered as a potential failure mode.*

## I. Introduction

The current tokamak design for the ARIES project includes a divertor that employs tungsten as a structural material [1]. As shown in Fig. 1, the design features steel inserts in the channels, but all other materials are tungsten or a tungsten alloy. This design was adopted in order to maximize the performance of the device. The high temperature capability of the tungsten permits a large allowable surface heat flux and makes the structure tolerant of transients, such as those caused by ELMS, but the choice carries with it some risk. Tungsten is a relatively low ductility material and is thus difficult to machine and susceptible to fracture. In this paper, we explore the mechanics of these components with the goal of establishing the feasibility of using tungsten as a structural material in a high heat flux fusion component. Specifically, we assess the impact of fracture and thermal creep during steady-state and transient operation.

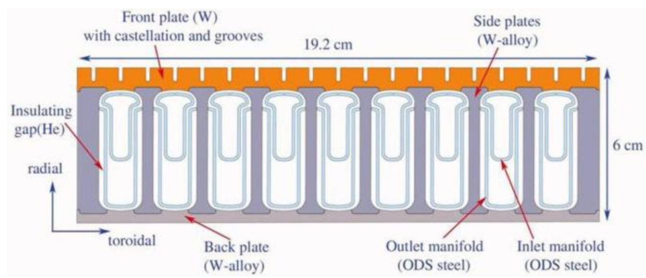



Fig. 1. Cross section of the ARIES divertor.

## II. Steady-State Thermal and Structural Analysis

A thermal analysis is required to provide temperature inputs to the structural analyses. In this section we present the steady state thermal analysis for the peak heat flux expected in the divertor. The analysis is carried out with ANSYS, a commercial finite element code. 3-D elements are used and a representative section of the component is modeled, employing appropriate boundary conditions to simulate the effects of the surrounding structure and coolant flows. The parameters used in the analysis are given in Fig. 1 along with the resultant structural temperatures. Using these parameters and internal convection conditions gleaned from gleaned from more complex fluid flow analyses [1], the peak tungsten temperature is found to be 1980 C. These temperature results were then transferred to the 3-D structural models. The material models for the structural simulations included both temperature dependent properties and plasticity.

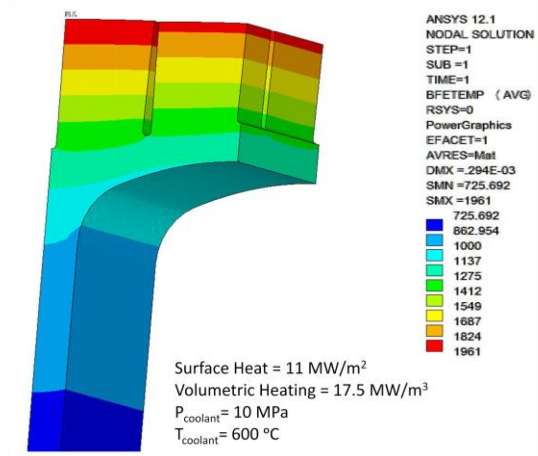



Fig. 2. Steady state full power heating conditions and resulting temperatures (C).

### III. Crack-Free Stresses

To identify likely locations of critical cracks in the tungsten structure, we first ran a crack-free stress analysis. The stresses in the x-direction (horizontal at the top and perpendicular to the flow direction) are shown in Fig. 3. As shown, the peak tensile stress is on the inside surface of the tungsten and is approximately 484 MPa. Based on this result, a semi-elliptical crack is inserted in the model on the inner surface of the cut face, as shown in Fig. 4.

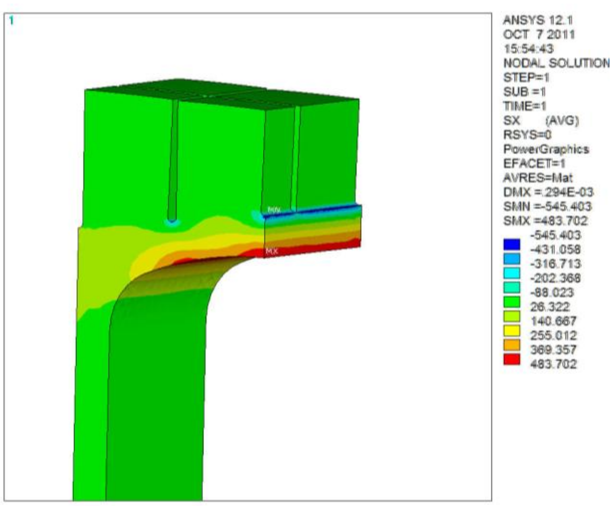



Fig. 3. Stresses in the x-direction at full power (MPa).

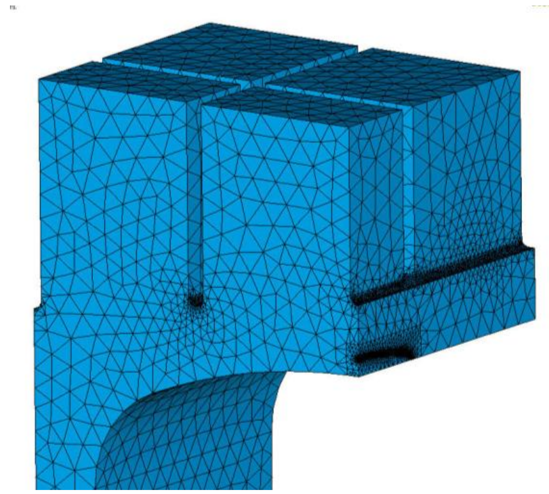


Fig. 4. Close-up view of finite element model showing semi-elliptical crack.

### IV. Fracture Modeling

Fracture is modeled using quarter-point elements at the crack tip (Fig. 4). The J-integral is calculated using a line integral around the crack tip and an equivalent stress intensity factor is calculated for comparison to conventional fracture toughness values. These values are presented parametrically in Fig. 5 for a variety of crack geometries. For reference, the toughness of pure tungsten is around 10 MPa-m$^{1/2}$ at 400 C [2], though it is fairly sensitive to processing.

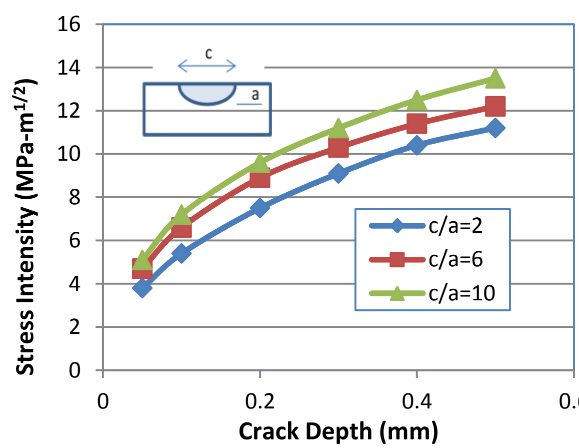



Fig. 5. Stress intensity factor as a function of aspect ratio for a semi-elliptical crack on the inner surface of the divertor. In this plot, *c* represents the width of the crack and *a* represents the depth.

### V. Varying Crack Location and Orientation

As we must determine the crack orientation prior to modeling, other locations must be considered to ensure that we are modeling the critical crack in the structure. To this end, we introduced a crack on the same inner surface, but rotated 90 degrees. The stress intensity factors for a semicircular crack are shown in Fig. 6. As expected, these values are less severe than those shown in Fig. 5.

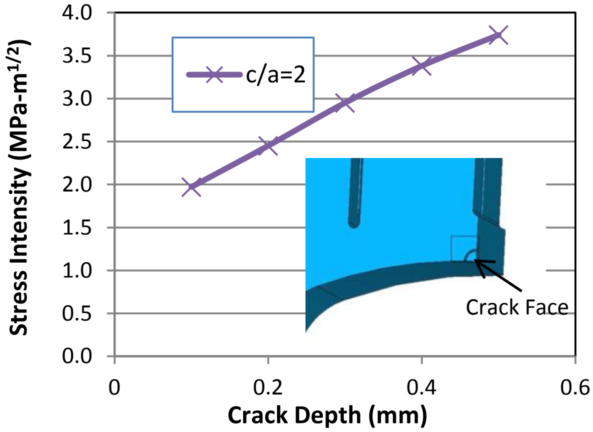



Fig. 6. Stress intensity factors for a crack oriented 90 degrees relative to the crack shown in Fig. 3.

## VI. Fracture Potential at Shutdown

Since there is some permanent plastic deformation associated with the analyses carried out in the previous two sections, residual stresses are expected upon removal of the heat load. These residual stresses will tend to reverse sign relative to the stresses at full power, so one would expect tensile stresses at the notch between tiles after shutdown (based on the results shown in Fig. 3). For this situation, a crack on the opposite surface, between two tiles was modeled. The stress intensities calculated this condition  are shown in Fig. 7.

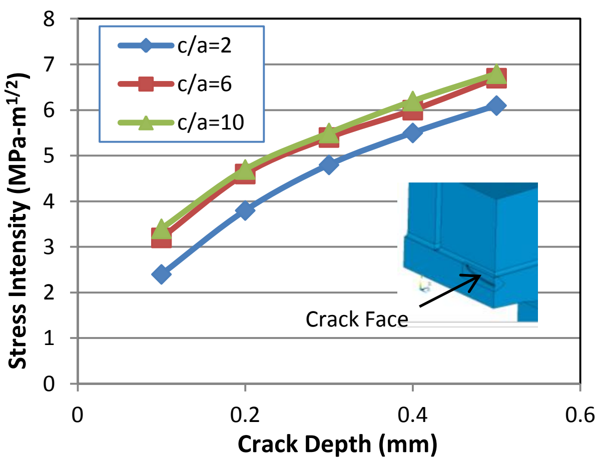
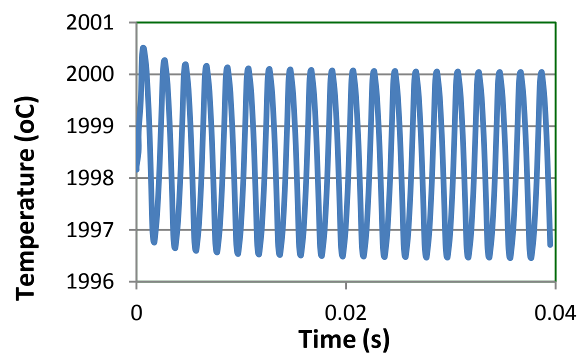


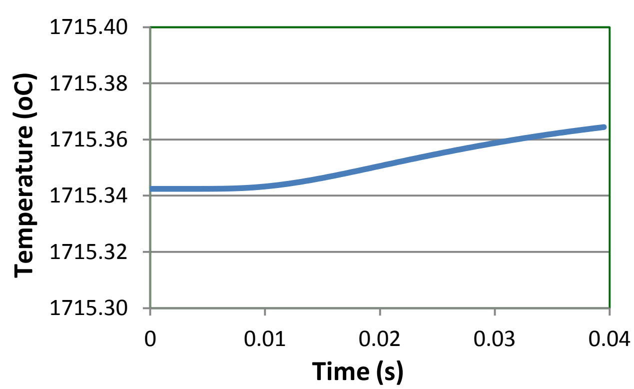

Fig. 7. Stress intensity factors at shutdown for a crack between the tiles.

## VII. Thermal Transients

Plasma-facing structures are expected to experience transient heat loads that will complicate their failure analysis and design. As an example, consider edge-localized modes (ELMs), which deposit heat on those surfaces in bursts. To address the implications of ELMS, we must address both sub-surface and surface effects. To estimate the importance of sub-surface effects, we applied a transient heat load with a triangular pulse shape for 20 cycles to the divertor surface and observed temperature fluctuations at the surface and 2.5 mm below the surface. In this simulation, the peak divertor heat flux was varied +/- 20%, a far smaller fluctuation than one would expect in a typical ELM. However, it still permits conclusions regarding the relative importance of these transients to temperature and stress fluctuations below the surface. As shown in Fig. 8, this simulation exhibits a fluctuation of approximately 3.5 degrees at the surface, while there is no detectable fluctuation 2.5 mm below the surface. Hence, we conclude that ELMs with a 1 ms pulse width are not expected to cause subsurface failure in these structures.




(a)




(b)

Fig. 8. Temperature variation at surface (a) and 2.5 mm below the surface (b) as a result of a triangular heat pulse with peak variations of +/- 20% of the nominal heat flux.

To estimate the surface effects of ELMs, we must use a more realistic model for the anticipated heat load variations. More specifically, we estimate that the divertor structures will experience peak heat loads of approximately 1.95 MJ spread over a triangular heat pulse with a 0.4 ms rise time and a 0.8 ms fall time. We first let the divertor model reach steady state and then applied the ELM load to the surface for a single pulse. The time-dependent temperatures resulting from this simulation are shown in Fig. 9. This model displays some melting, so it was modified to incorporate the latent heat of fusion for tungsten. As can be seen in this figure, this ELM load will melt approximately 20 microns of the surface, given the 3410 C melting temperature of pure tungsten. Further design considerations are necessary to explore options for eliminating melting during these events.

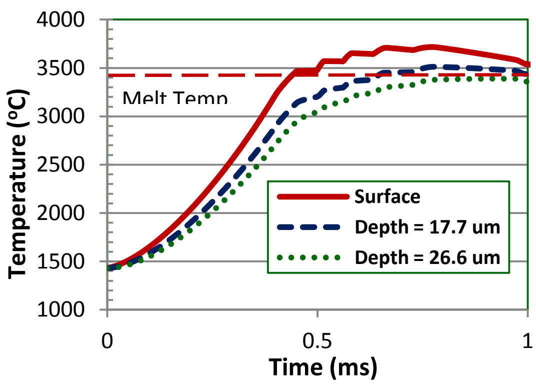



Fig. 9. Time-dependent temperatures near the divertor surface resulting from a single ELM load.

### VIII. Thermal Creep

Despite the high melting temperature of tungsten, thermal creep can still be a design issue as we push the performance as high as possible. To address this, we have introduced a thermal creep constitutive law into the finite element models. Creep data for tungsten in the temperature range (1000 - 1400 C) [3] were fit to a power law creep model resulting in the following:

$$\epsilon = 156 \left[e^{\frac{-53370}{T}}\right] \sigma^5 \qquad (1)$$

This describes a power law creep model with strong dependence on both temperature and stress. Hence, small design changes can have dramatic impact on the stress and deformation results. Initial runs with this model assumed steady state conditions (without ELMS) and applied the nominal 11 MW/m$^2$ surface heat flux on the dirvertor surface. The model was run for 1800 hours and the time dependent displacement at the center of the coolant channel is shown in Fig. 10. These displacements (5 mm) are excessive and are accompanied by very high creep strains.

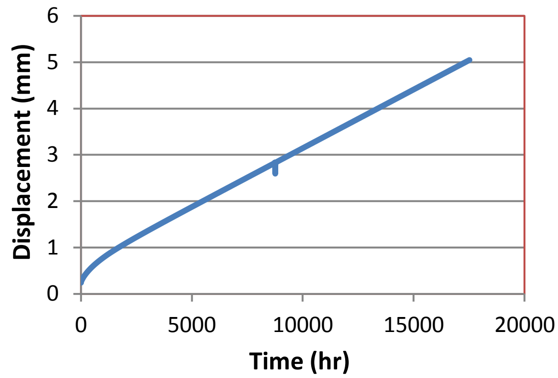



Fig. 10. Maximum divertor displacement for nominal steady-state heat and pressure loads.

To reduce the thermal creep rates in this structure, we must reduce either the stress or the temperature. To reduce the stress, the pressure is the key parameter, because the secondary thermal stresses relax out and do not contribute in any significant way to the long-term, accumulated creep strains. To reduce the temperature, one can lower the bulk coolant temperature (though this will decrease the difference between the minimum structure temperature and the recrystallization temperature of the tungsten) or reduce the surface heat flux.

To explore this effect the surface heat flux was reduced from 11 MW/m$^2$ to 6.7 MW/m$^2$. This reduces the peak surface temperature from 1980 C to 1433 C. Due to the nonlinearity of the creep relation, this creates a dramatic reduction in the creep rates. As shown in Fig. 11, the peak creep strains after two years are less than 0.1%, which is below the allowable amount. This figure also shows the stress relaxation (saturation of thermal creep strain) of the thermal stresses and the long-term impact of the pressure stresses.

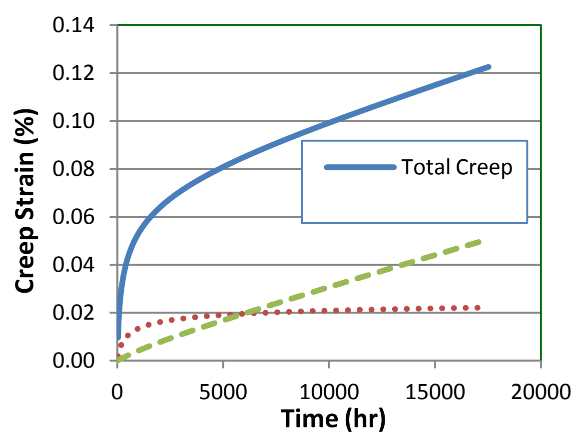



Fig. 11. Creep strains after two years for three cases: pressure loading only, thermal loading only, and both

loads together. These results are for a location on the inner surface of the coolant channel, near the top.

The sensitivity of this creep strain to variations in the surface heat flux and the coolant pressure are shown in Fig. 12. In either case, the baseline load is varied about the baseline value and the normalized creep strain is plotted as a function of the varying parameter (normalized to the baseline value).

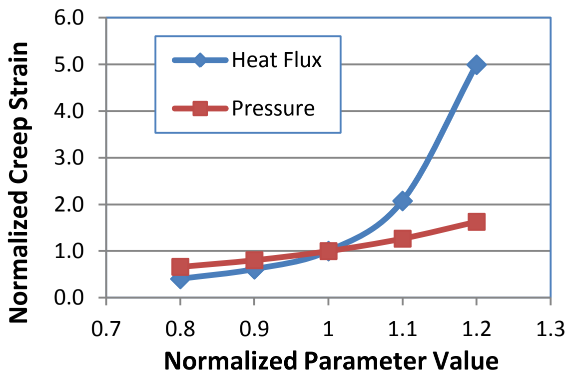



Fig. 12. Normalized variation in peak creep strain for different values of the surface heat flux and coolant pressure. The baseline flux is 6.7 MW/m$^2$. The baseline pressure is 10 MPa.

Finally, the depth of the notch between tiles was varied to assess the impact on the creep rate. This modification effectively reduces the tile thickness, thus increasing the thermal stress and decreasing the pressure stress. As shown in Fig. 13, reducing the notch depth from 3 mm to 2 mm decreases the creep strain after two years by about 23%.

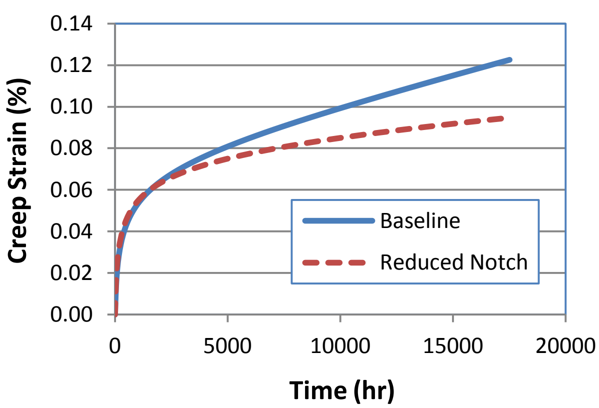



Fig. 13. Creep strain over a two year period for the nominal design and a design with a reduced depth notch.

## IX. Conclusions

A series of analyses are carried out to assess the ability of an all-tungsten divertor to provide an adequate life in a tokamak. Fracture analyses indicated that the ARIES divertor design can tolerate cracks of sufficient size to be detectable prior to operation. Preliminary analysis of edge-localized modes indicates melting of the divertor surface, but design changes are under consideration that may alleviate the surface damage. Finally, thermal creep has been considered as a possible failure mode. Again, preliminary calculations indicate that, without prudent design, creep rupture will likely lead to failure. Parametric studies indicate that there are several options for design changes that will alleviate this as a failure mode.

## ACKNOWLEDGMENTS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