Fracture and Creep in the All-Tungsten ARIES Divertor

Jake Blanchard
University of Wisconsin – Madison

(presented by Mark Tillack)

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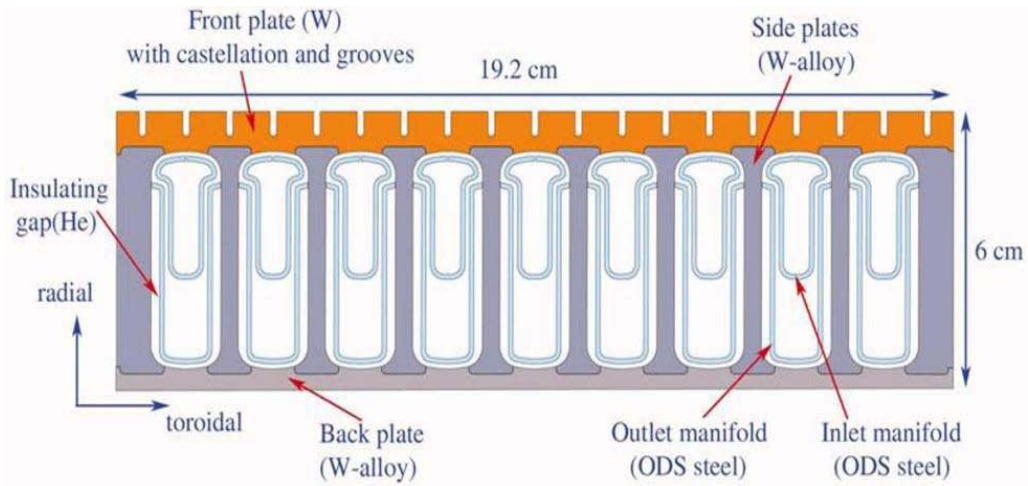
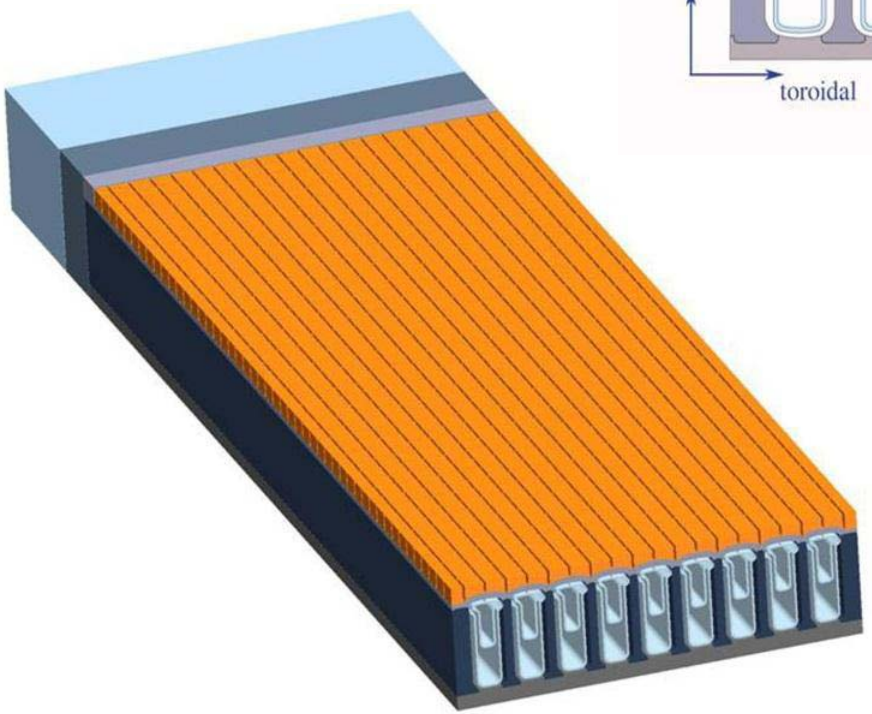
Introduction

- The ARIES Project is exploring the feasibility of using tungsten as a structural material for plasma-facing components
- For this analysis, we assumed the material is pure tungsten, but alloys may be necessary
- This talk addresses two key failure modes that must be addressed by these designs
  - Fracture
  - Thermal creep

We examined the ARIES plate divertor design





Temperature distributions were simulated using ARIES design loads with simplified convection cooling

$q''=11\ MW/m^2$

$q'''=17.5\ MW/m^3$

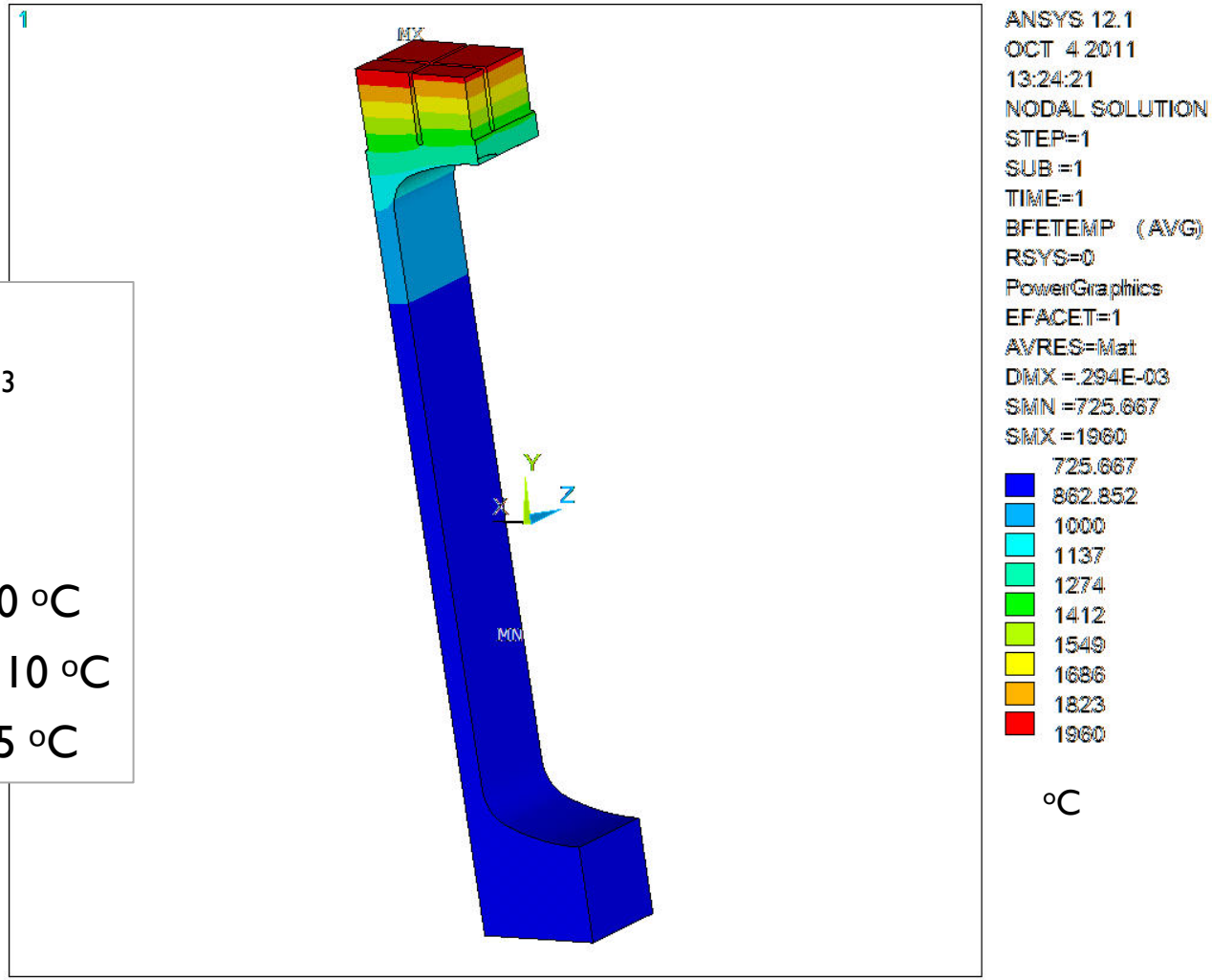
$P=10\ MPa$

$T_{coolant}=600\ ^oC$

$Max.T_{armor}= 2000\ ^oC$

$Max.T_{structure}=1310\ ^oC$

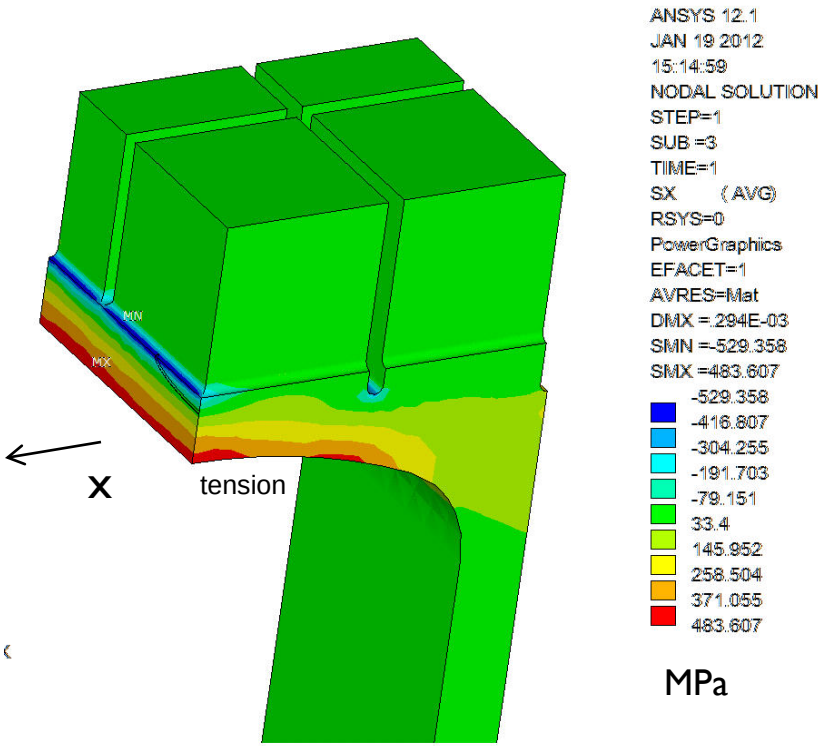
$Min.T_{structure}=725\ ^oC$



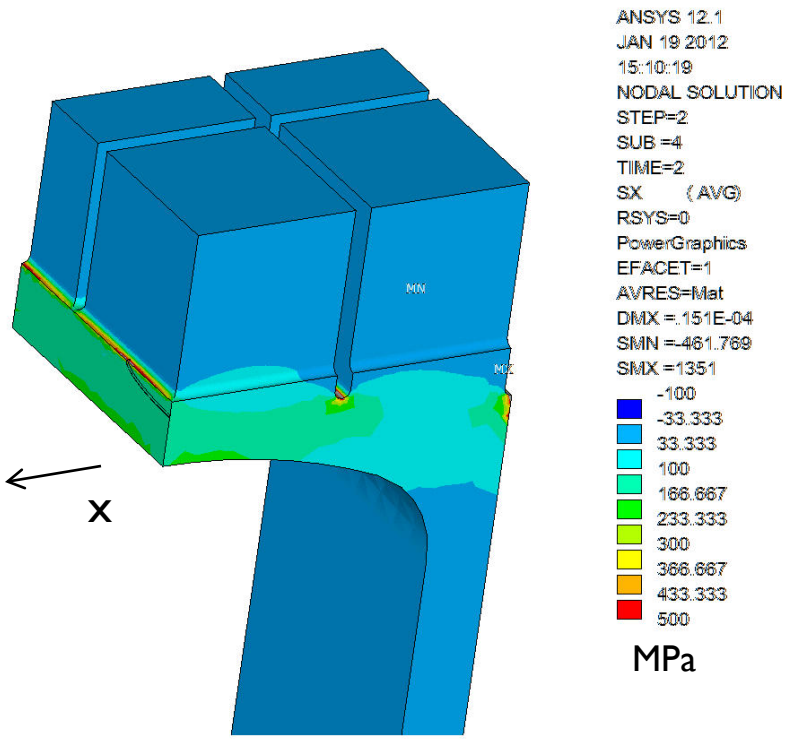
Stresses in uncracked structure identify regions of concern

- During operation: tensile stress along the cooling channel, compressive stress in the grooves.
- High tensile stress occurs at the base of the grooves after cool-down, resulting from plastic deformation.

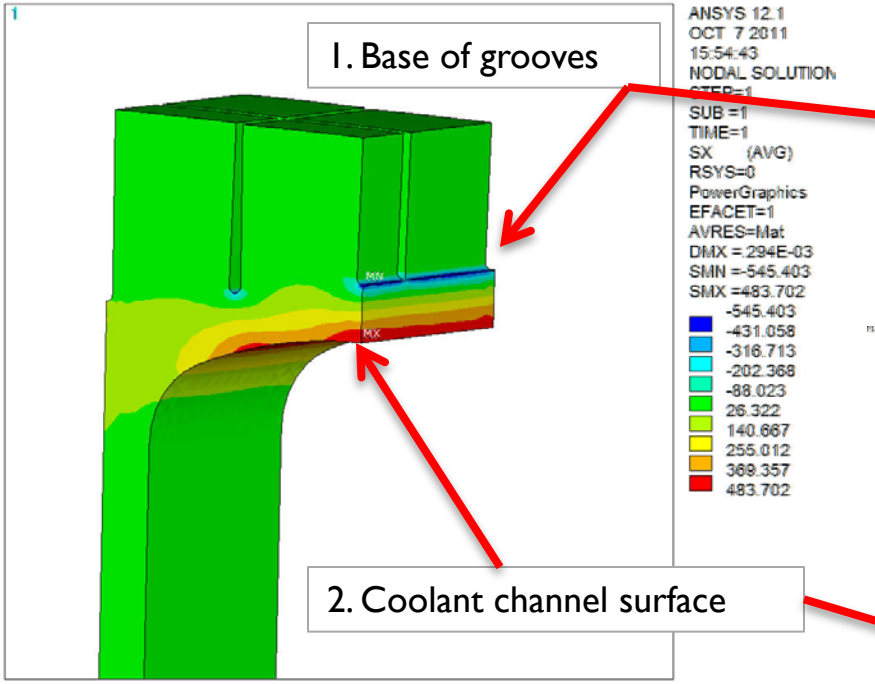
X- Stress Distribution when Hot (MPa)



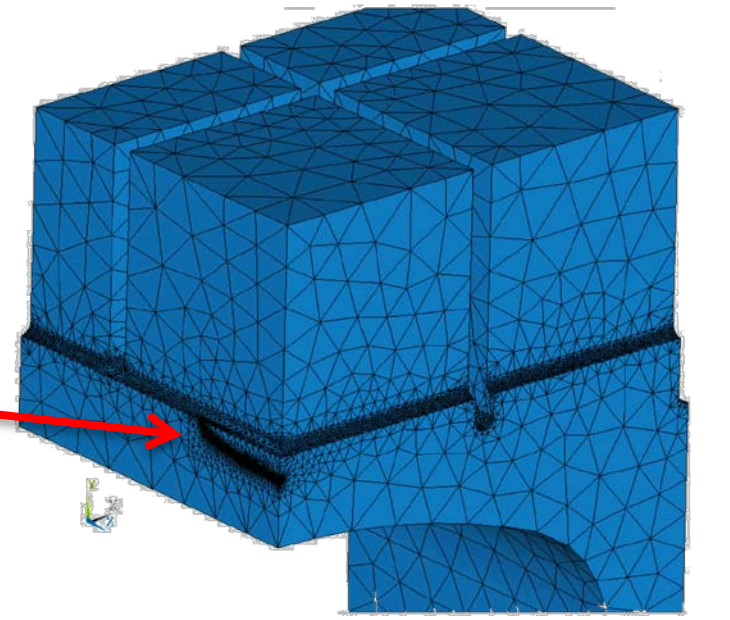
X- Stress Distribution after Cool-down (MPa)

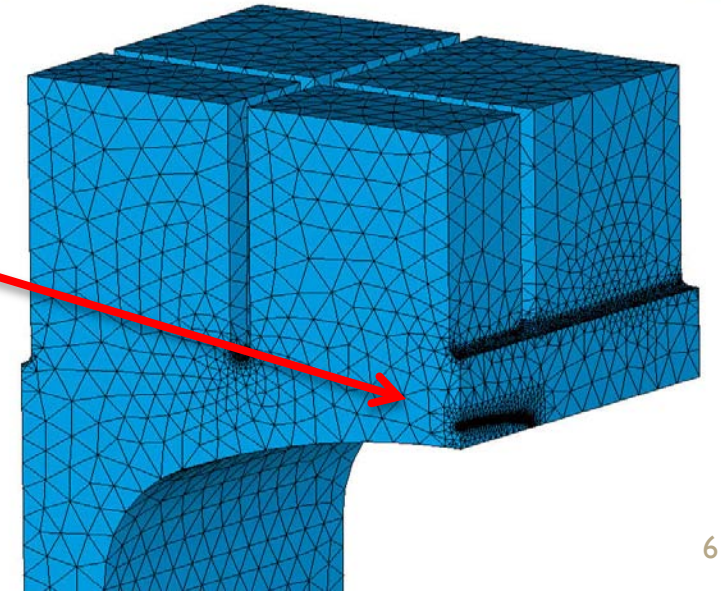


Simulated cracks were introduced in high-stress regions

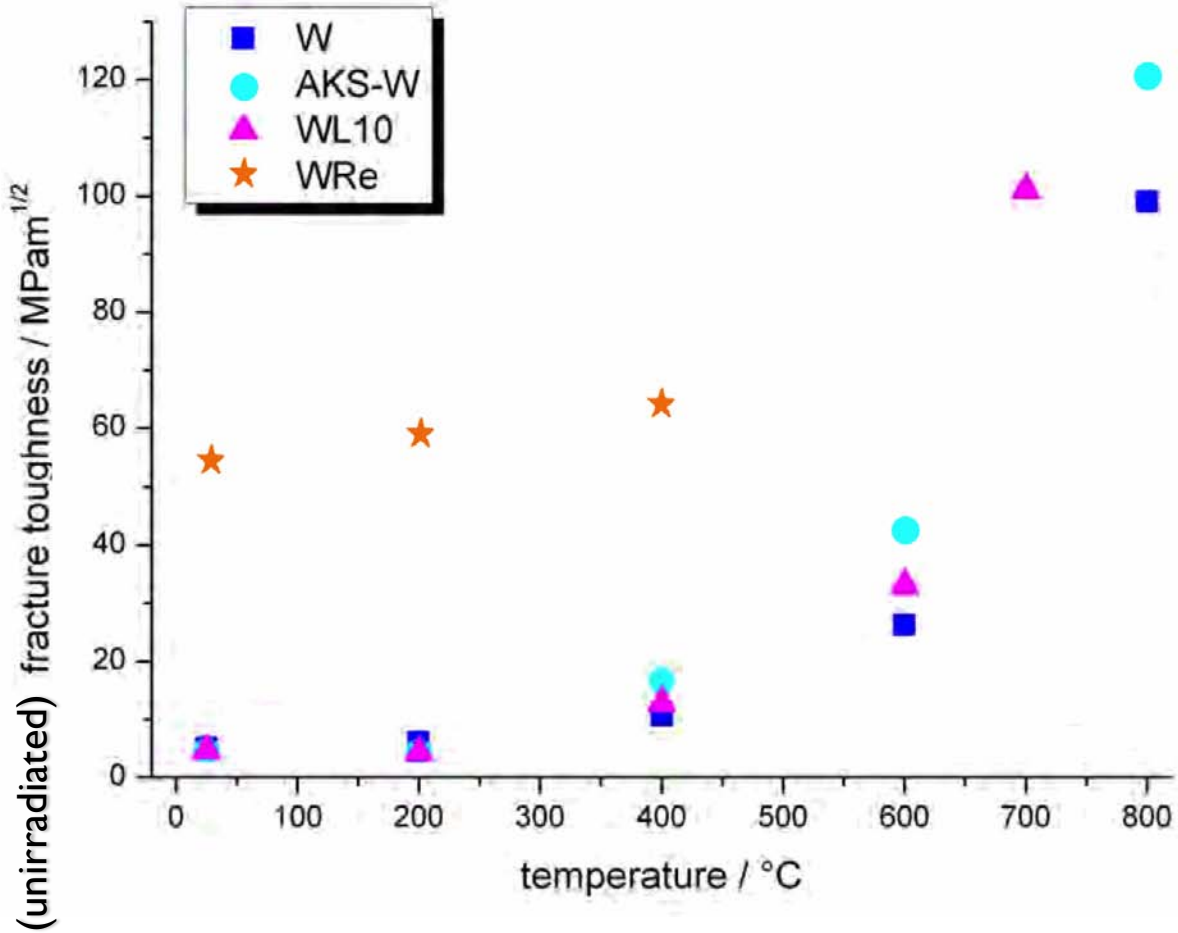


Crack-Free Stress State



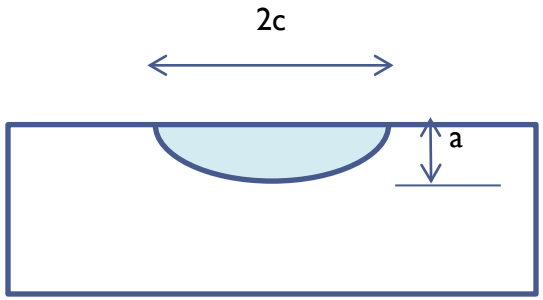


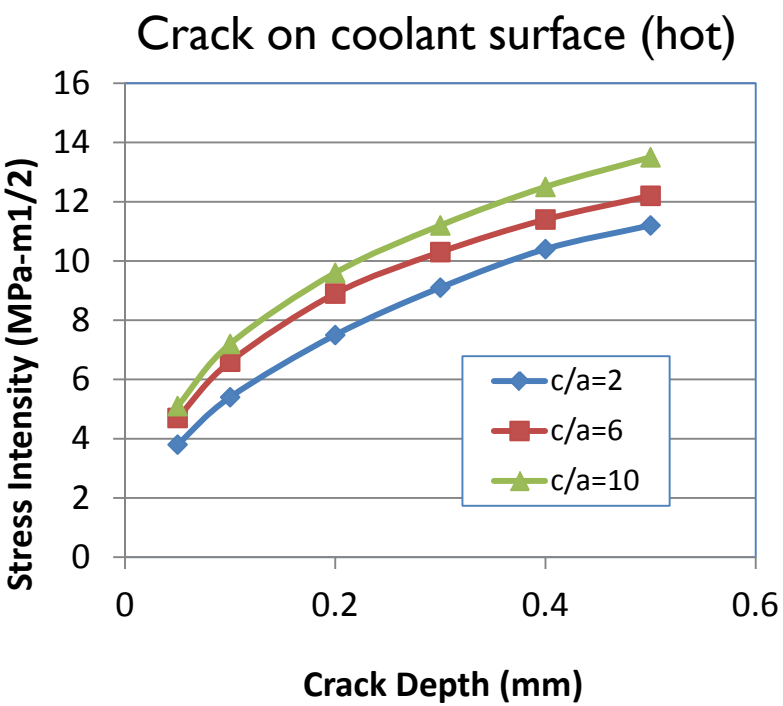
Stress intensity should remain below the fracture toughness

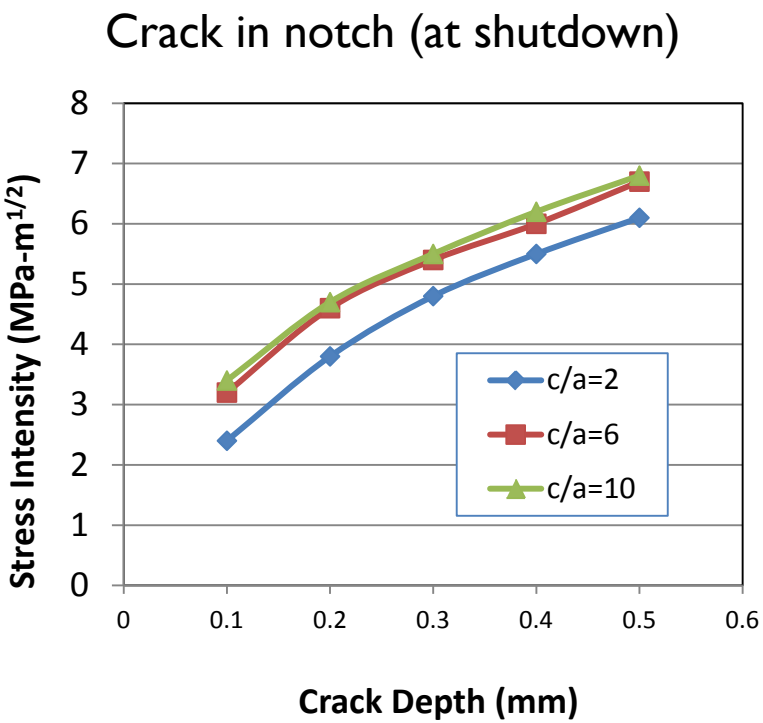


B. Gludovatz, S. Wurster, A. Hoffmann, R. Pippan, "Fracture Toughness of Polycrystalline Tungsten Alloys." 17th Plansee Seminar 2009, Vol. 1.

Fracture Results

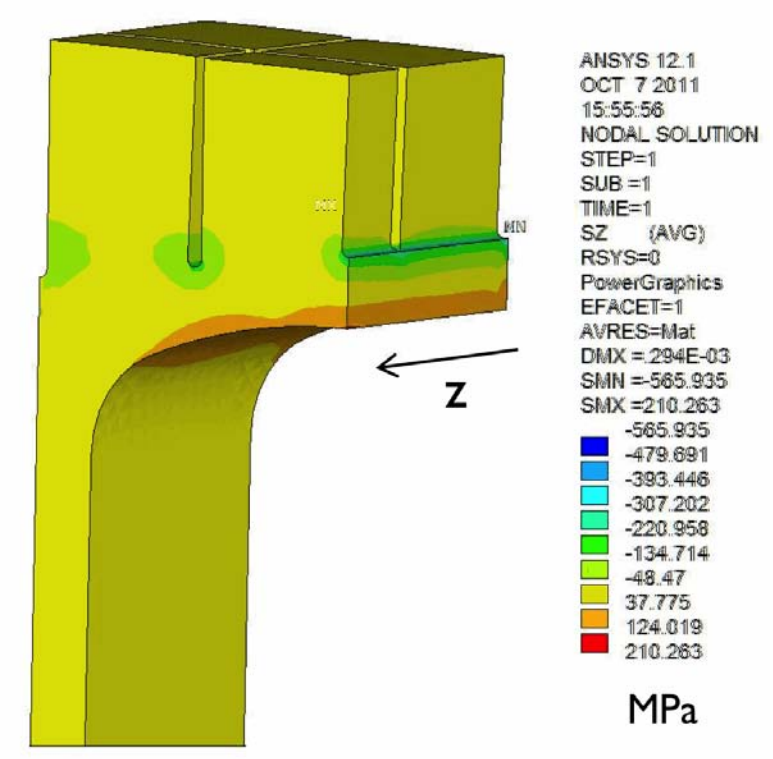


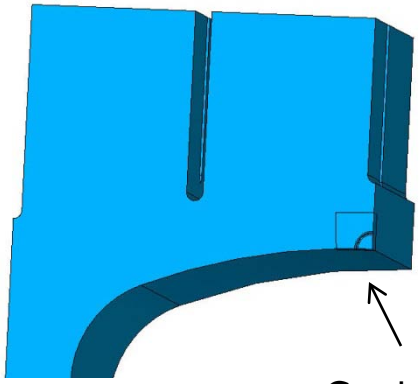


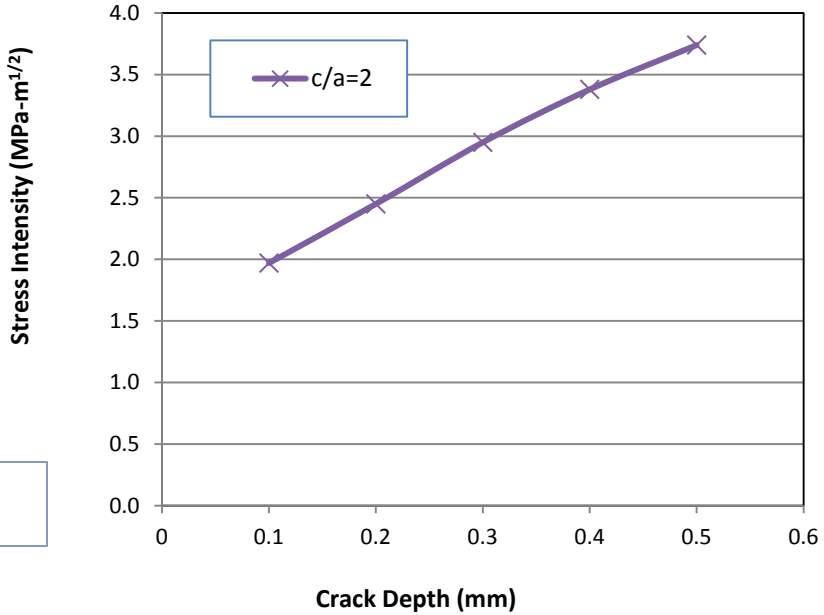


Stress intensities for crack perpendicular to coolant flow direction

Z- Stress Distribution when Hot







Lower stress intensities are obtained

Conclusions on fracture

- Stress intensity is highest at full power.
- Critical crack is in the notch between "tiles" under shutdown conditions.
- This may change if thermal creep is taken into account.
- Fatigue (growth rate) has not yet been explicitly included.

Thermal Creep

Thermal analysis predicts temperatures in the 1100 – 1300 °C range in the W structure

- While structural temperatures are only ~0.4 T/T_m data indicate that pure tungsten can creep at these temperatures.
- Power law creep model was added to ANSYS analysis to evaluate creep behavior

q''=11 MW/m^2

q'''=17.5 MW/m^3

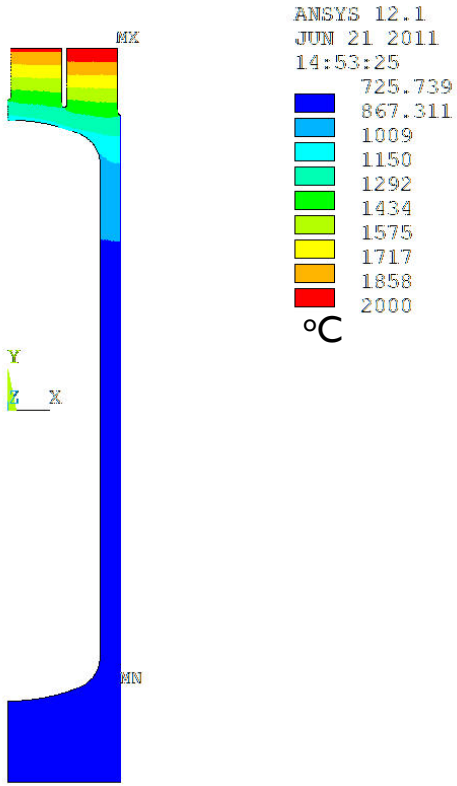
P=10 MPa

$T_{coolant}$=600 °C

Max. T_{armor}= 2000 °C

Max. $T_{structure}$=1310 °C

Min. $T_{structure}$=725 °C



Large uncertainties exist in creep strain rate data

- Most W creep data is for higher temperatures and lower stress
- Limited available data for temperatures/stresses of interest

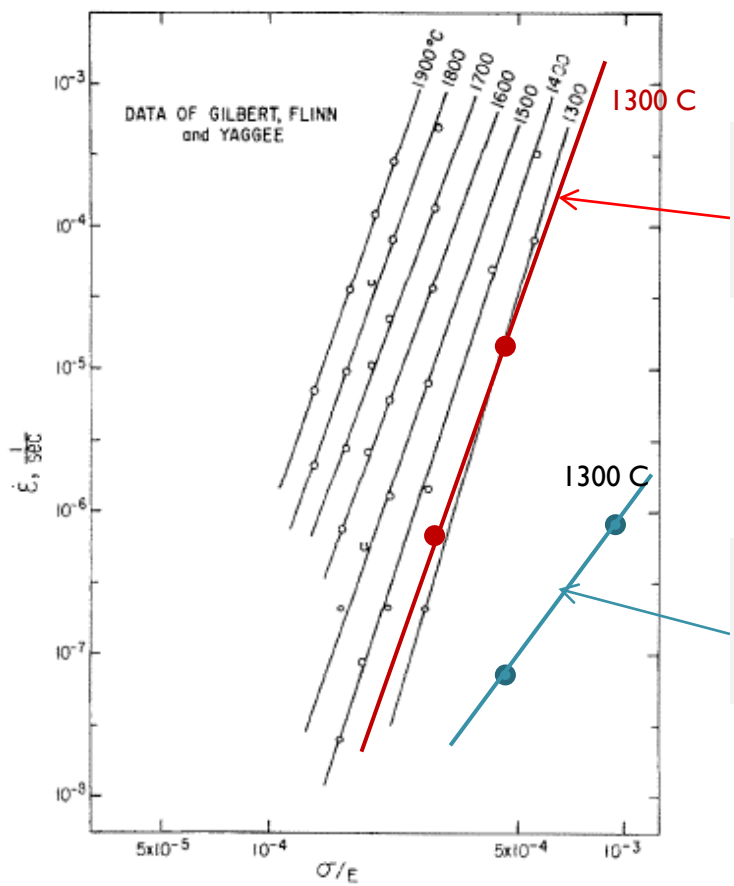


FIG. 4. Steady state creep rate of tungsten as a function of modulus corrected stress.

$$\dot{\epsilon} = 156 \times 10^{3} \left[e^{\frac{-53370}{T}} \right] \times \sigma^{5}$$

$\dot{\epsilon}$ = steady state creep rate, h^{-1}

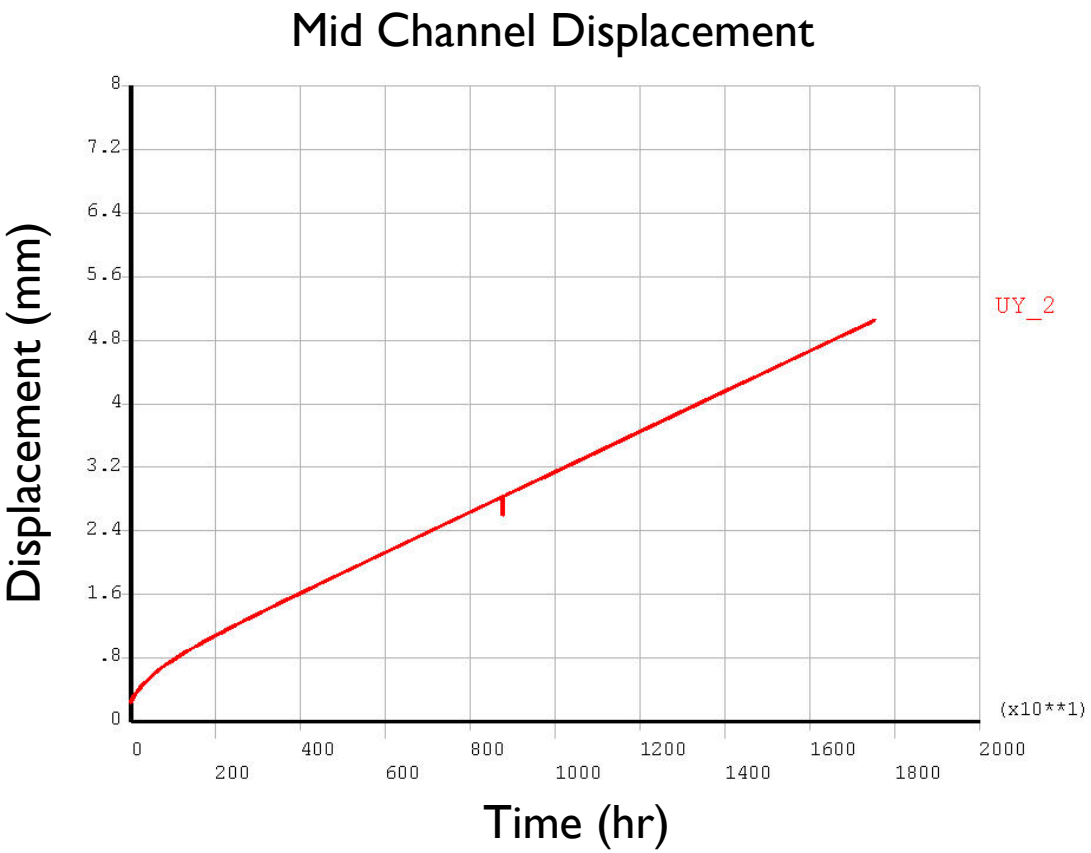
σ = creep stress, MPa, $\sigma \leq 20.0$ MPa

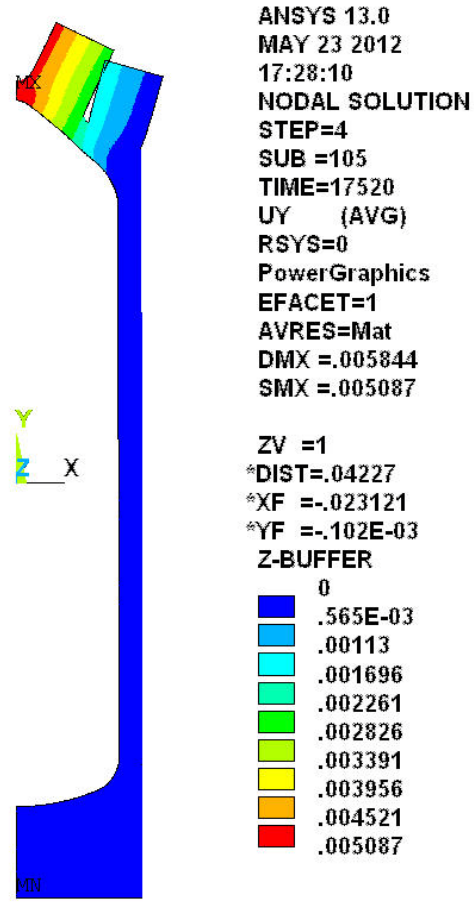
$1500 \leq T \leq 2900$, K

$$\dot{\epsilon} = 1.3 \times 10^{3} \left[e^{\frac{-53370}{T}} \right] \times \sigma^{3.53}$$

A. Purohit N. A. Hanan S. K. Bhattacharyya E. E. Gruber "Development of a steady state creep behavior model of polycrystalline tungsten for bimodal space reactor application." Argonne National Lab., IL 1995

Using the more conservative data, excessive creep deformation is obtained





Additional studies were performed using reduced heat flux

- Reducing the surface flux to a value of 6.7 MW/m^2 reduces the maximum armor temperature to 1433 ^oC
- Structure temperatures where creep occurs are in the 900-1000 ^oC range

q”=6.7 MW/m^2

q’”=17.5 MW/m^3

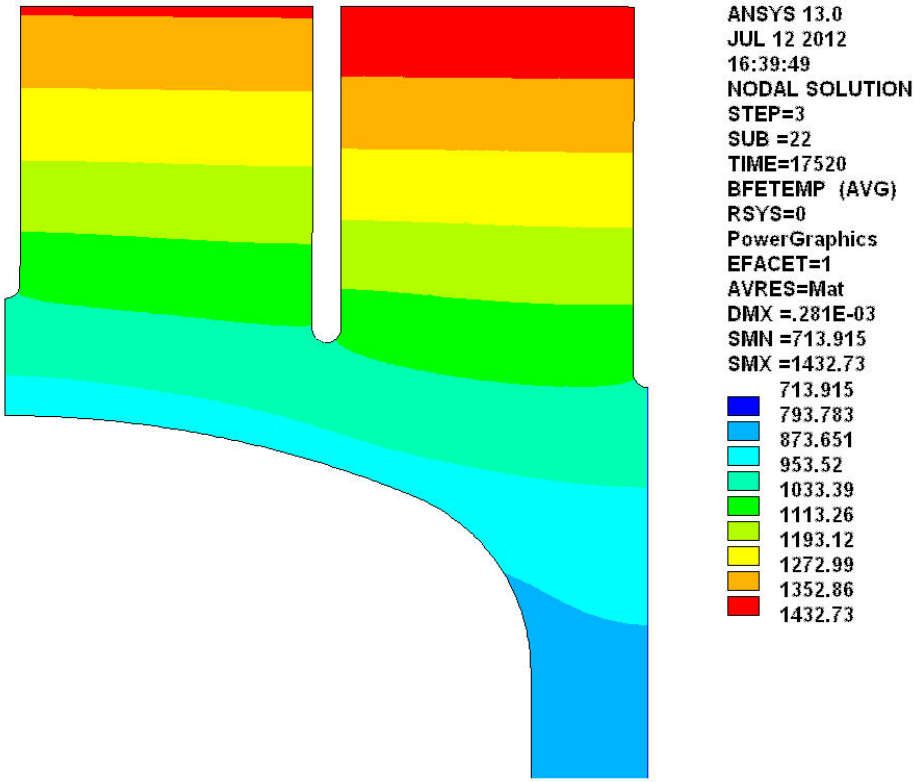
P=10 MPa

$T_{coolant}$=600 ^oC

Max. T_{armor}=1433 ^oC

Max. $T_{structure}$=1310 ^oC

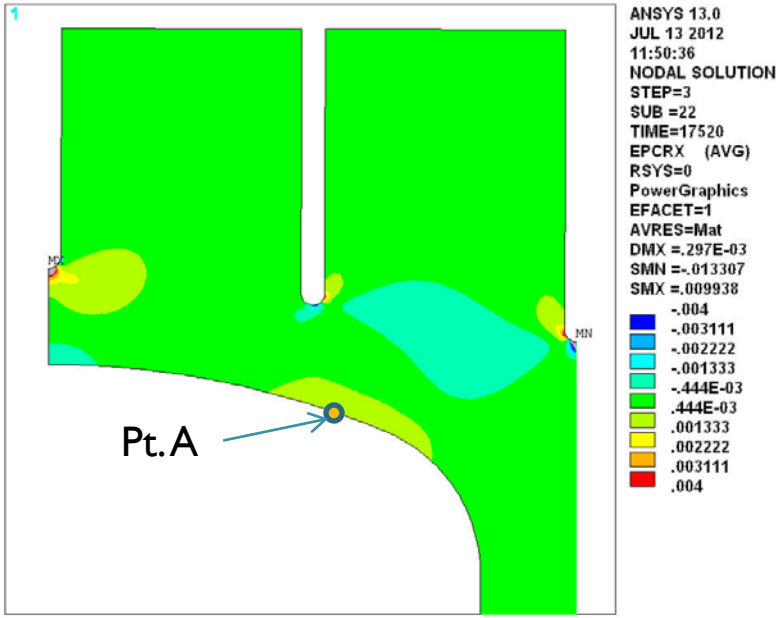
Min. $T_{structure}$=714 ^oC



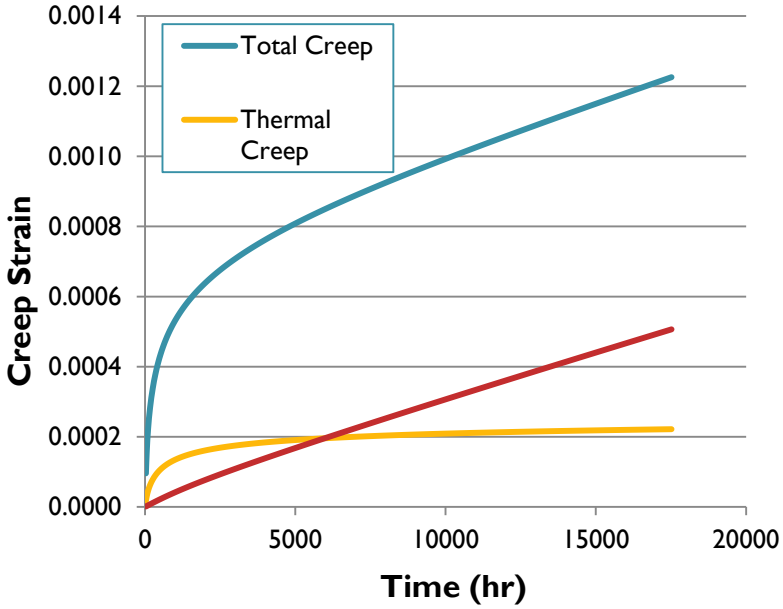
Creep behavior of tungsten armor over two year exposure

- Creep from combined thermal and pressure loads is considerably greater than sum of the individual components
- Thermal creep rate is initially high, but slows as stress is relieved. Pressure creep rates are constant.

Creep Strain After Two Years

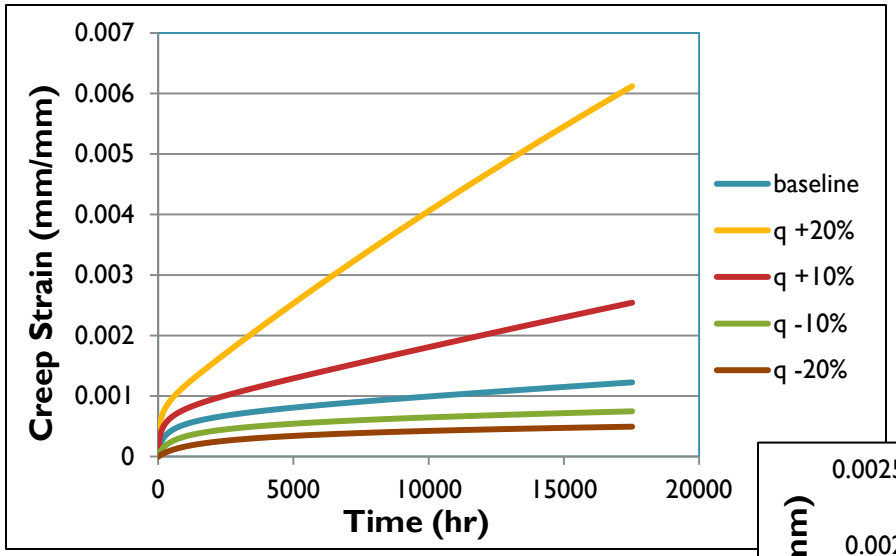


Total Creep Strain along with Pressure Only and Thermal Only Creep at Pt. A

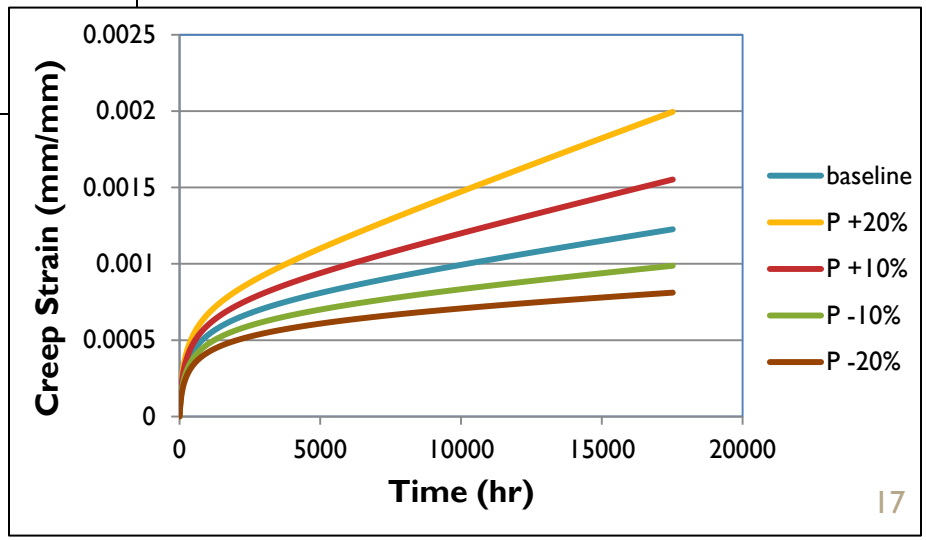


Sensitivity of Creep Rates to Changes in the Thermal and Pressure Loads

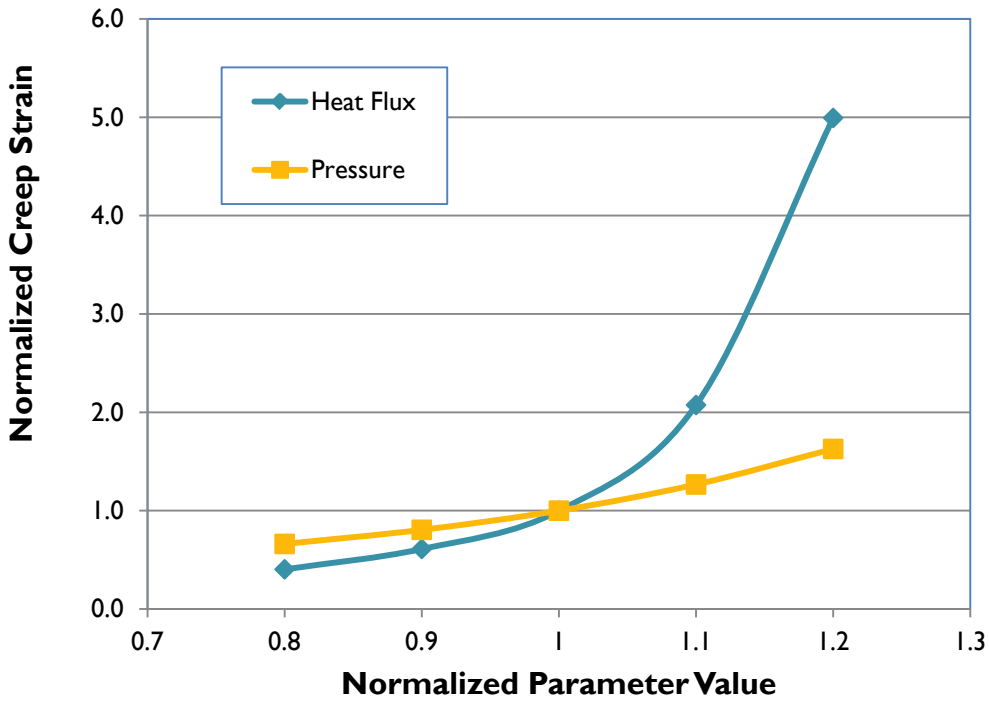
Creep Sensitivity to Surface Heat Flux



Creep Sensitivity to Coolant Pressure

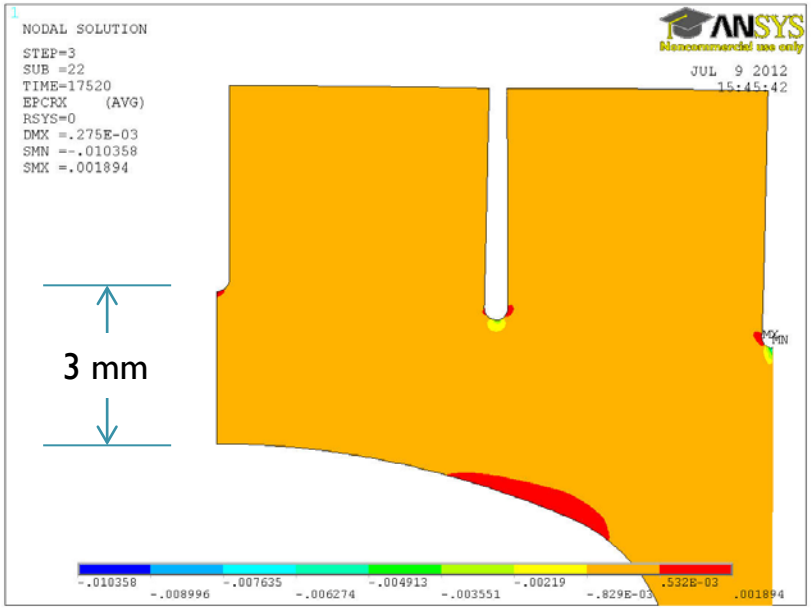


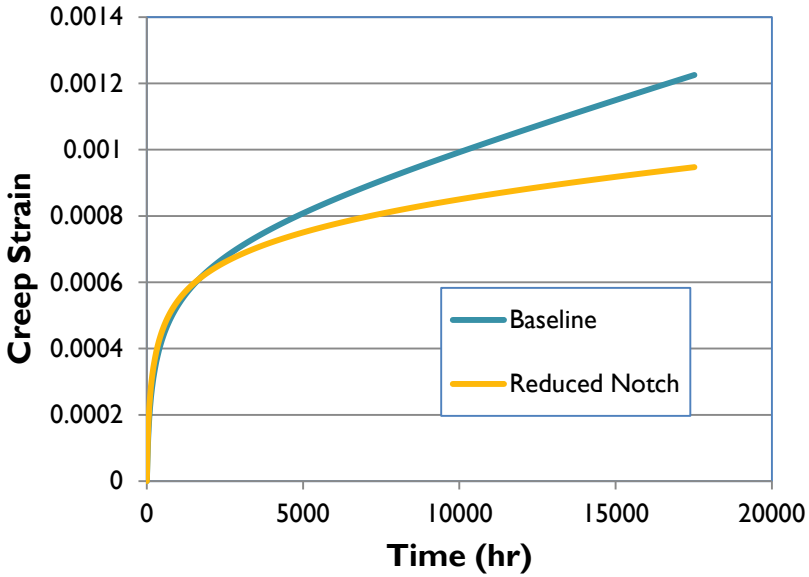
Results show creep rates are very sensitive to changes in temperature and stress



Reduce Tile Notch Depth by 1 mm

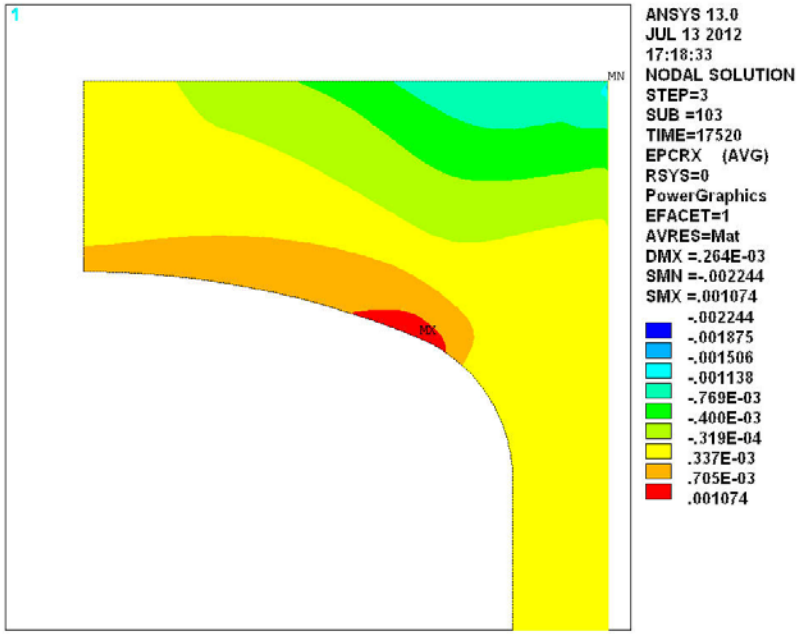
- Reducing the notch depth increases minimum wall thickness to 3 mm (from 2 mm) reducing pressure stress in wall with some increase in thermal stress.
- Two year creep strain is reduced by 23% and rate is also significantly reduced.

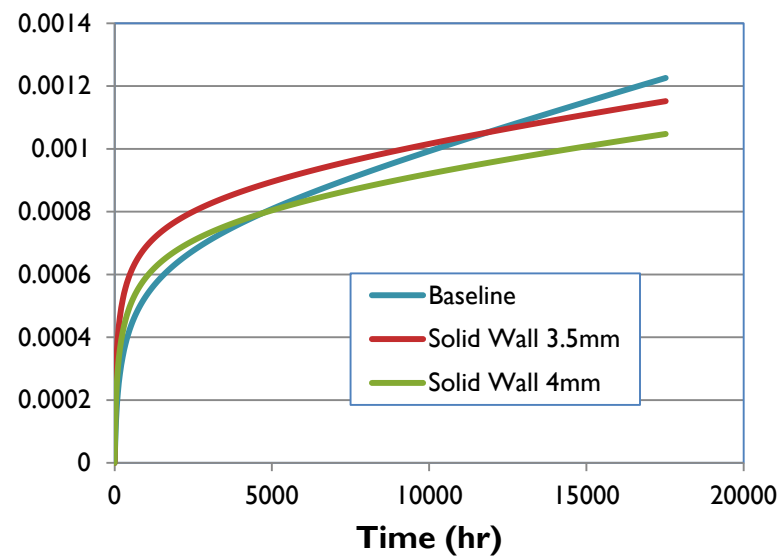




Remove Notch Completely

- Removing alleviates stress concentrations and lowers surface temperature. Thermal stresses increase however.
- Two year creep strain is reduced by 7% for a 3.5 mm wall and 15% for a 4 mm wall.
- 4 mm wall reduces maximum surface temperature by 162 °C *vs* baseline.





Conclusions on creep

- Creep appears to be a significant problem for design heat fluxes above 10 MW/m^2.
- Design changes can alleviate the problem to some extent, but
- Materials with higher creep strength are needed (compared with pure W).
- Reliable data are essential.

Data Needs

- Fracture toughness of tungsten (alloy)
  - As-manufactured, at temperature
  - Irradiated
- Crack growth rates (da/dN)
- Creep rates
- Creep rupture data
- Creep-fatigue interaction data