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Update on Structural Analyses: ELMS, Thermal Creep, and ITER Seismic Analysis

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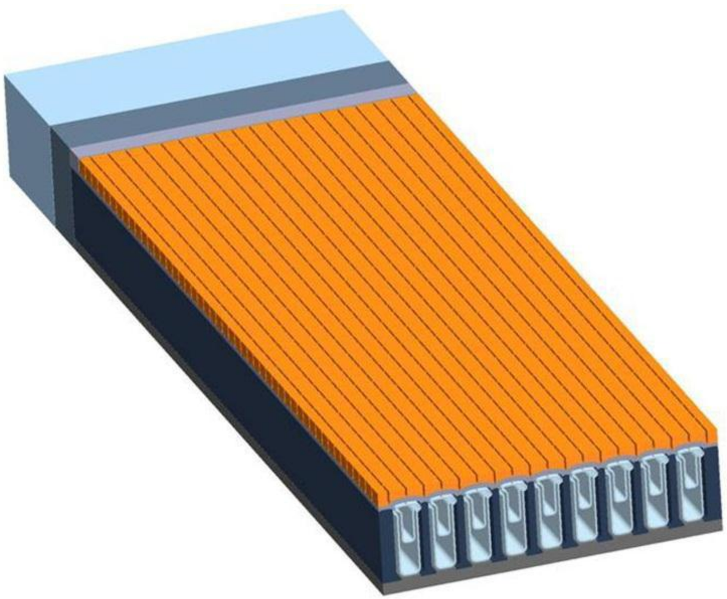
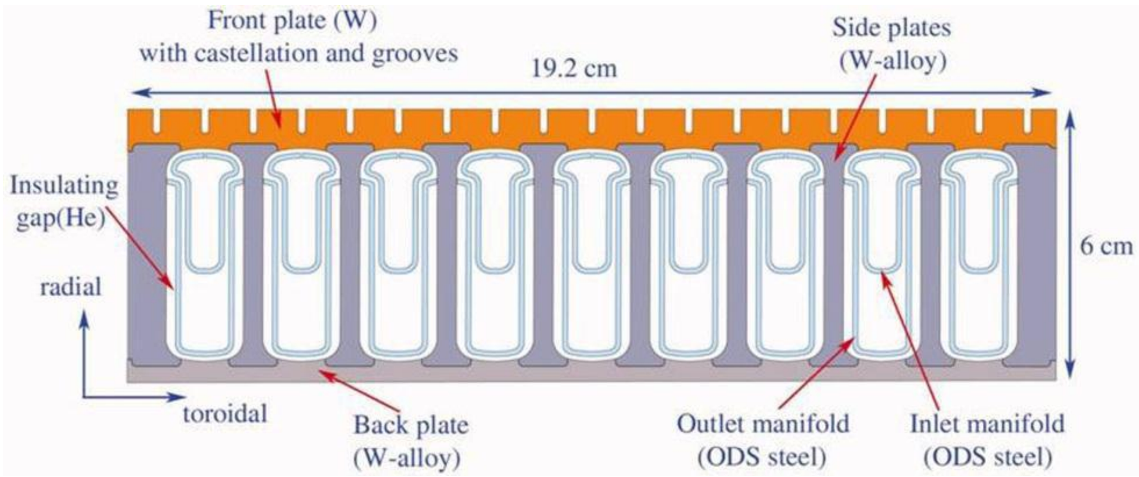
Tungsten HCFP(Helium-cooled Flat Plate) divertor

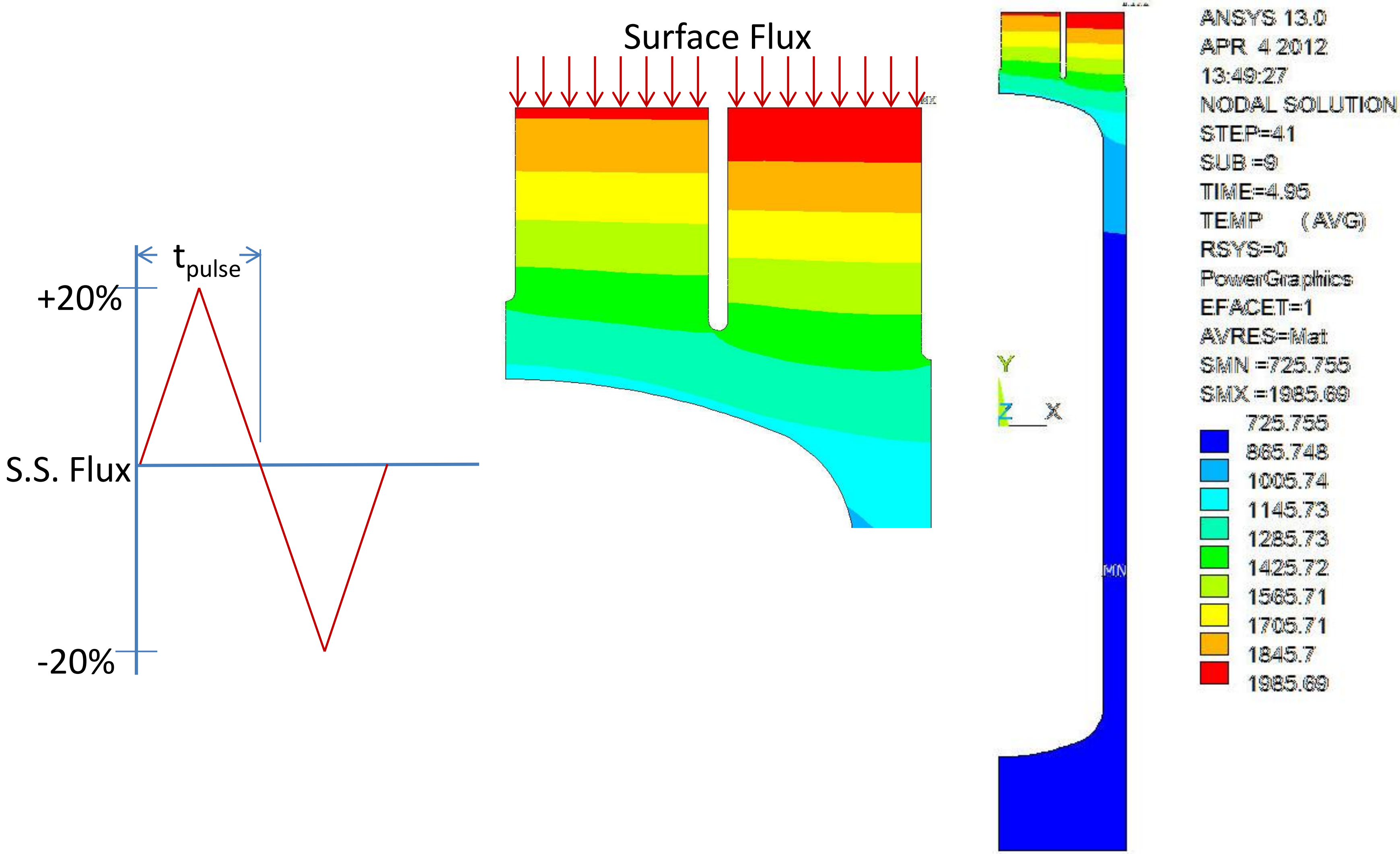




Thermal Transients

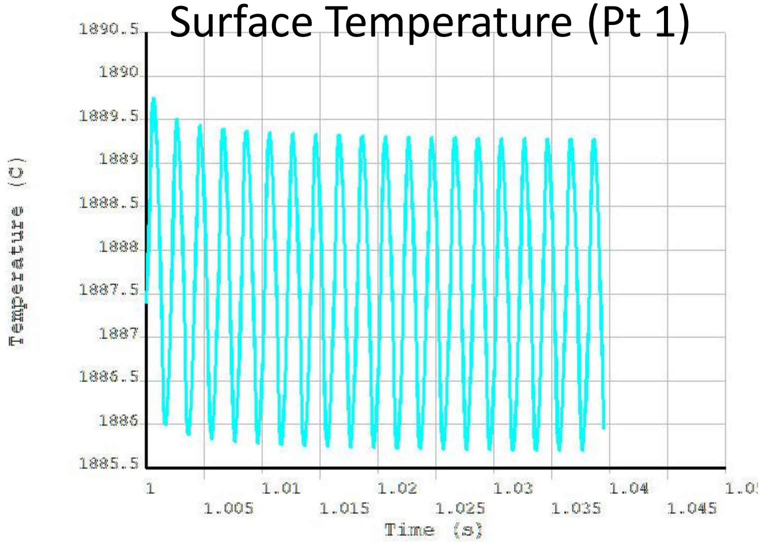
- We can expect fluctuations in surface heating due to ELMS.
- Will temperatures or stresses fluctuate in any significant way?
- We varied heating about the mean by $\pm$20%
- Cycle times were 1, 10, and 100 ms.

Thermal Response to Surface Heat Fluctuations

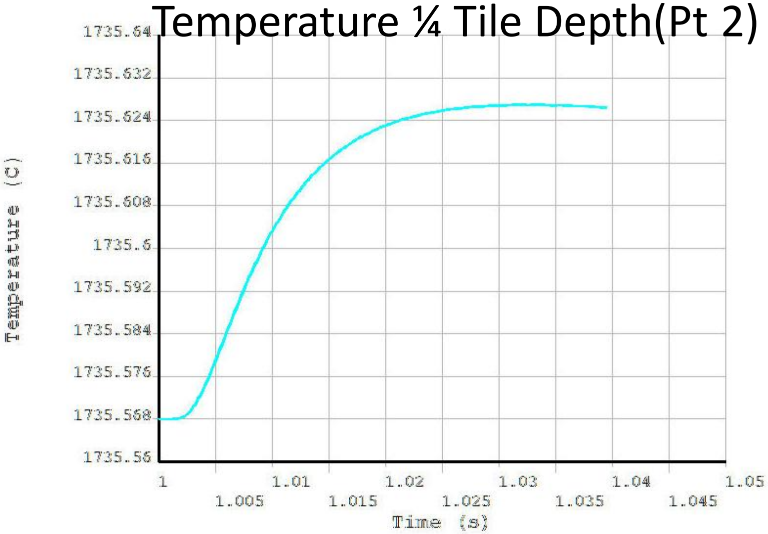


Pulse Time = 1 msec

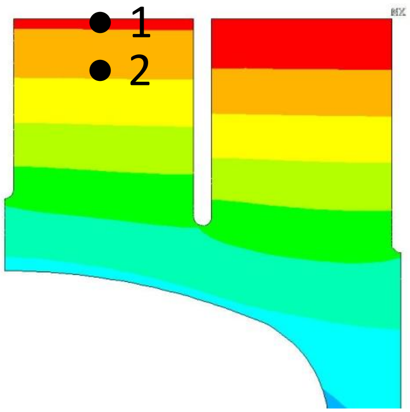
Surface Temperature (Pt 1)



Temperature ¼ Tile Depth(Pt 2)

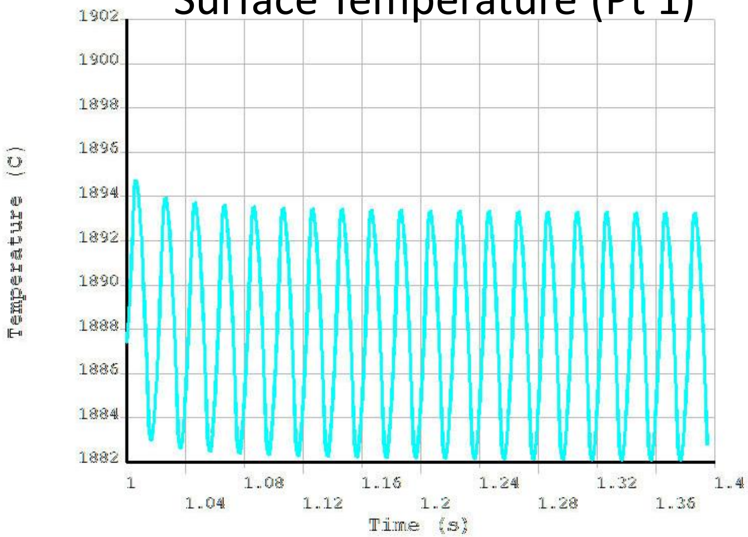


- Surface temperature fluctuates ~5 ^{o}C
- No cyclical variation seen at ¼ tile depth

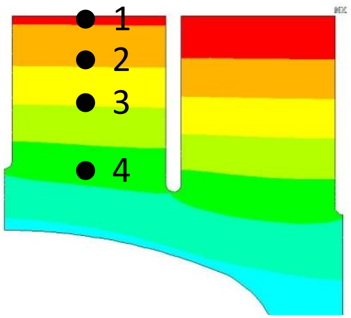


Pulse Time = 10 msec

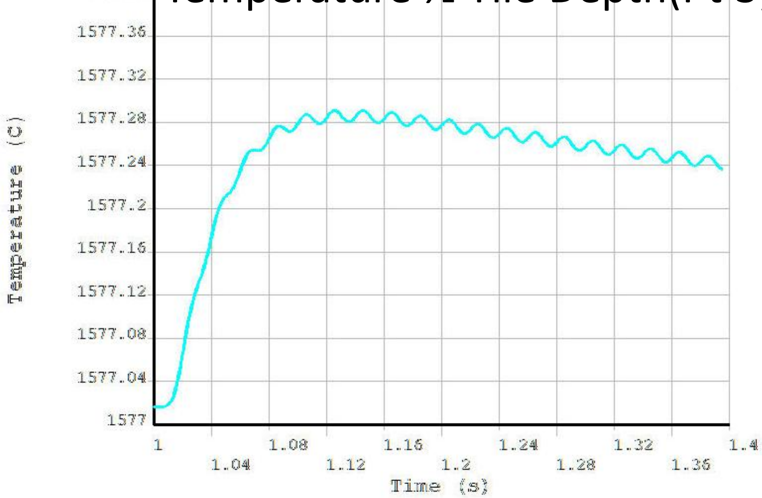
Surface Temperature (Pt 1)



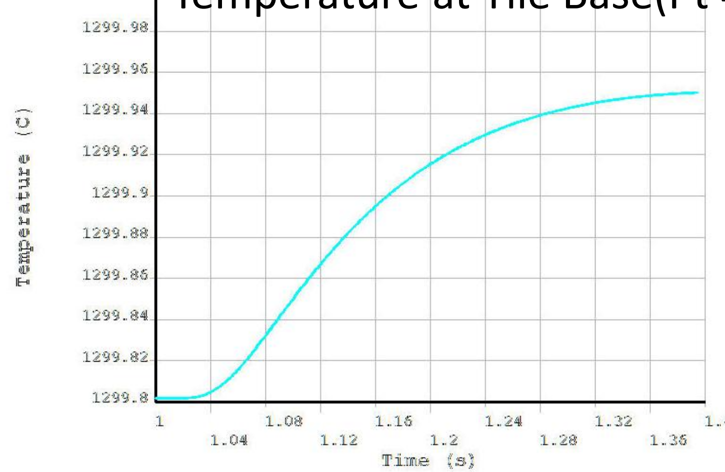
- Surface temperature fluctuates ~11 °C
- Small cyclical variation seen at ½ tile depth
- No cyclical variation seen at tile base



Temperature ½ Tile Depth(Pt 3)



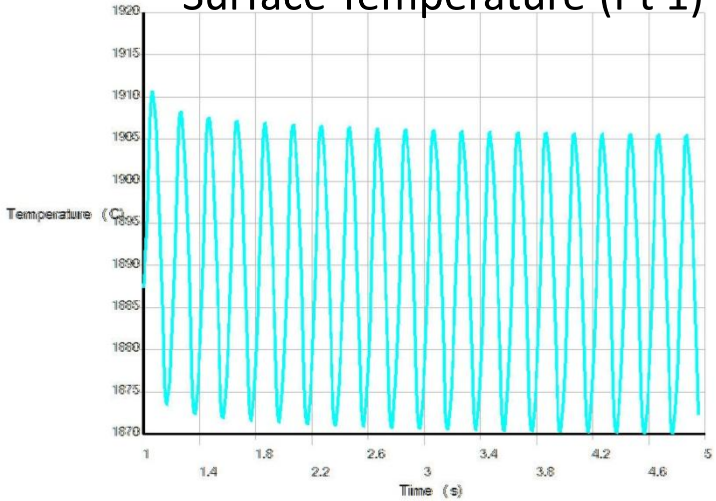
Temperature at Tile Base(Pt 4)

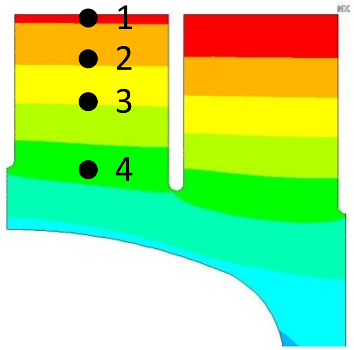


Pulse Time = 100 msec

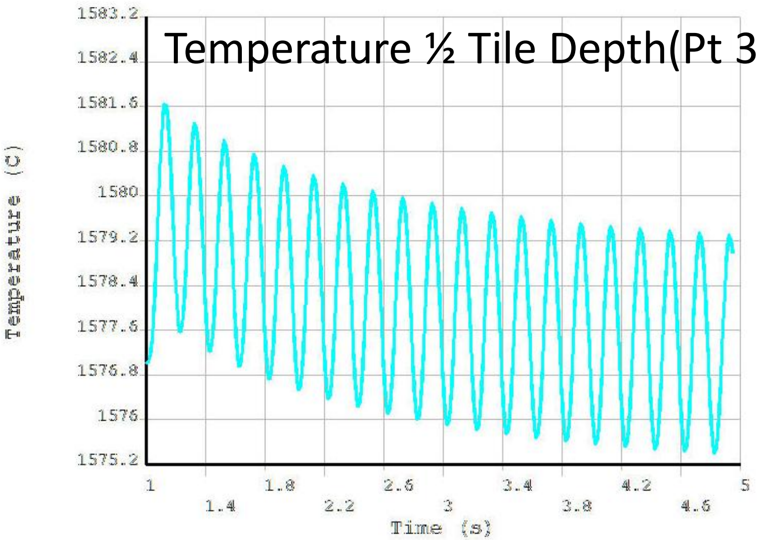
- Surface temperature fluctuates ~35 ^{o}C
- Temperature at ½ tile depth fluctuates ~4 ^{o}C
- Small cyclical variation seen at tile base

Surface Temperature (Pt 1)

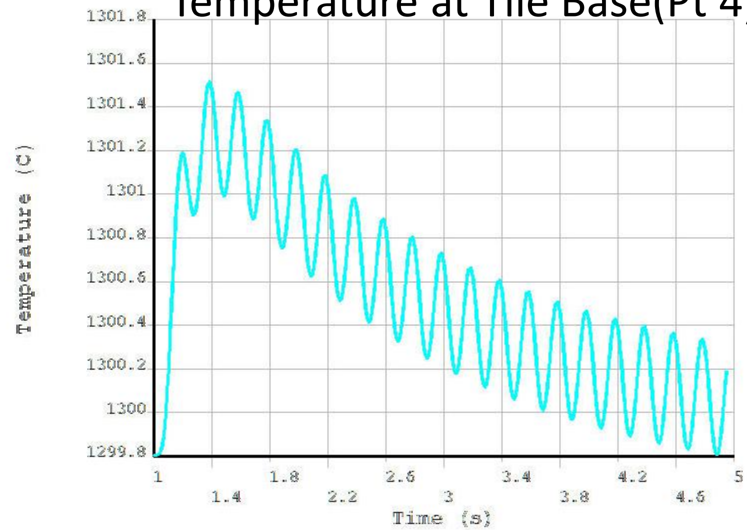




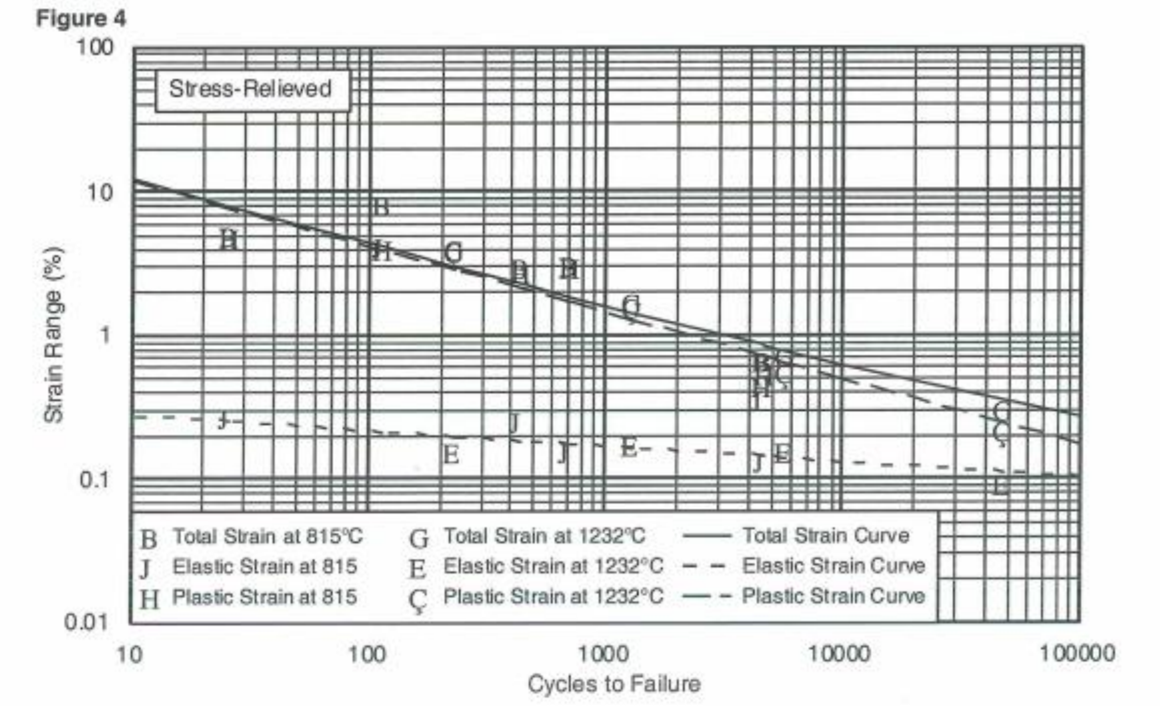
Temperature ½ Tile Depth(Pt 3)



Temperature at Tile Base(Pt 4)



High Cycle Fatigue Issue?



ITER Materials Handbook

Low Cycle Fatigue in Tungsten at 815 and 1232 C

I have not found high cycle fatigue data

High Cycle Fatigue in Tungsten Alloys

- Consider tungsten alloys:
- IT180 (W-3.5Ni-1.5wt%Cu)
- D176 (W-5Ni-2.5wt%Fe)
- Both show an endurance limit (210 and 425 MPa, respectively)

Fatigue Properties of Tungsten Heavy Alloys IT180 and D176
MS Thesis
Marc Miralda López, Patricia Lorenzo Paez
LUND UNIVERSITY, JUNE 2011

IT180

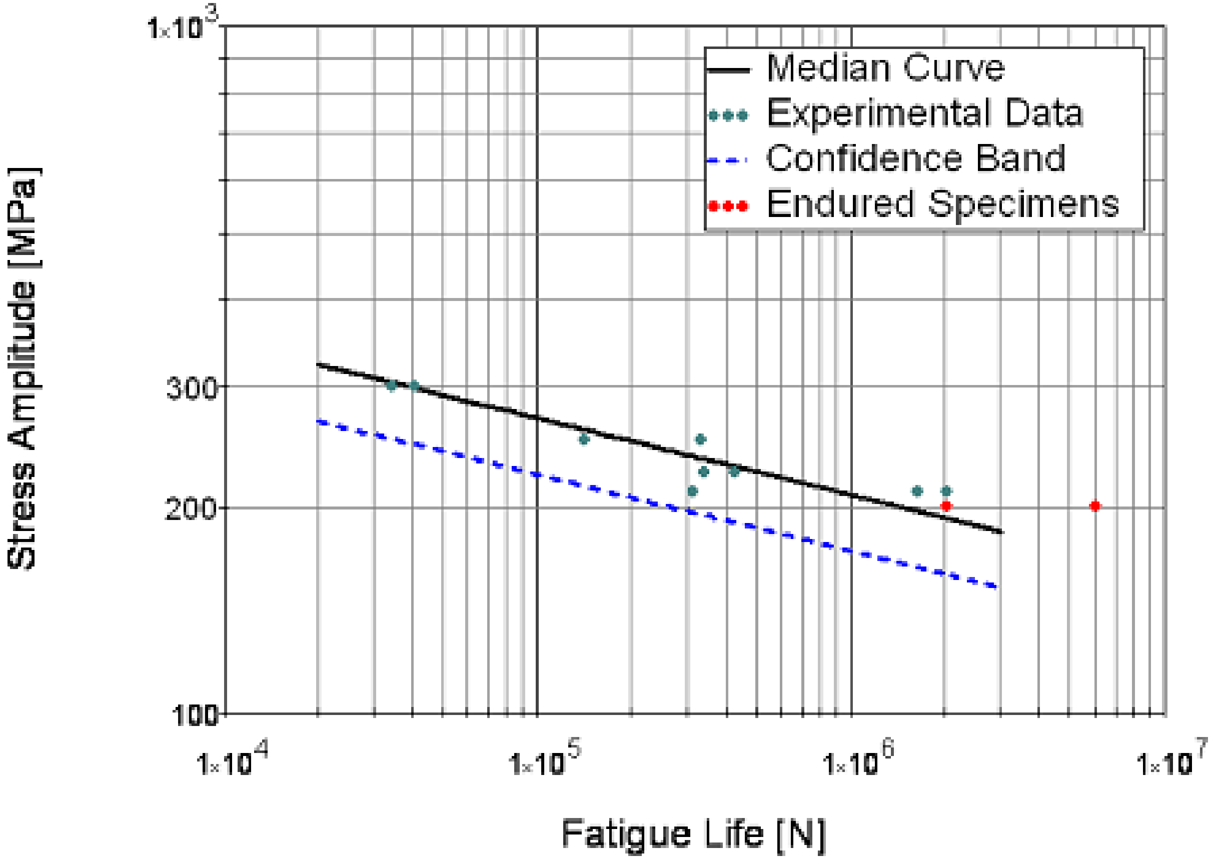


Figure 4.21 Experimental data of IT180 in the finite life region along with the statistical median curve and the confidence band.

D176

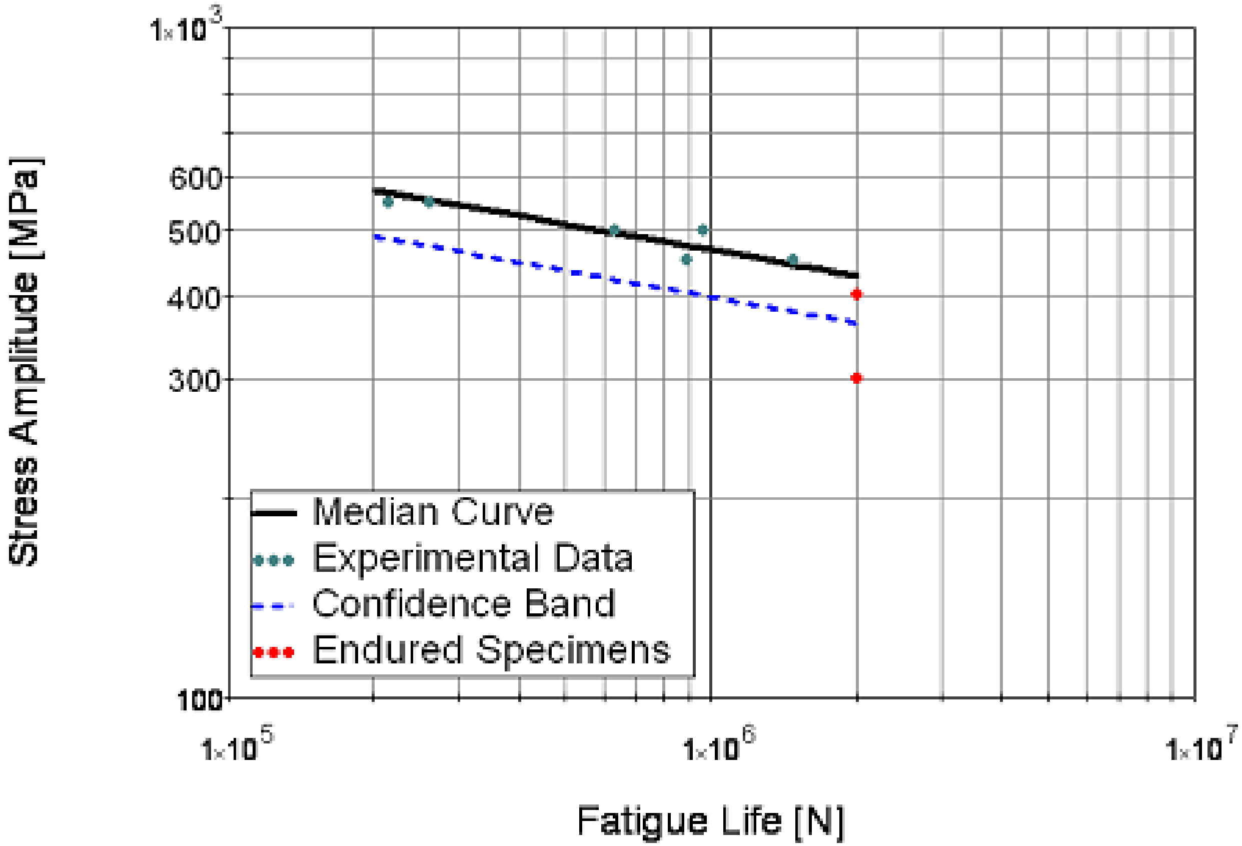


Figure 4.22 Experimental data of D176 in the finite life region along with the statistical median curve and the confidence band.

Thermal Creep

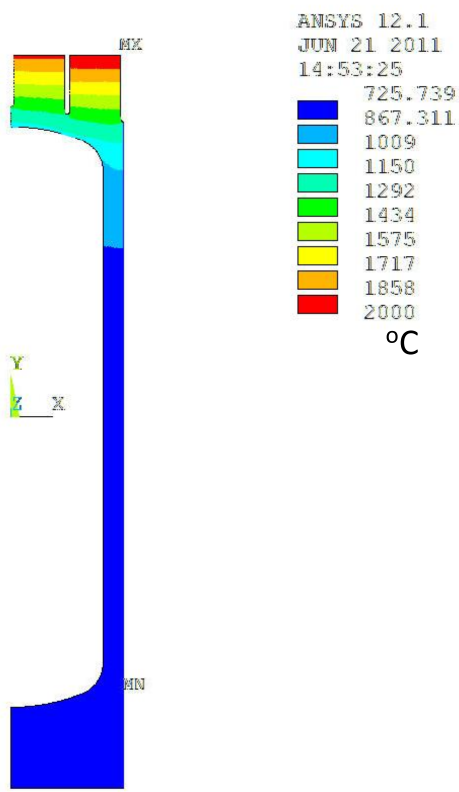
DL Robinson and OD Sherby, “Mechanical Behavior of Polycrystalline Tungsten at Elevated Temperature,” Acta Met, 17, 1969, 109

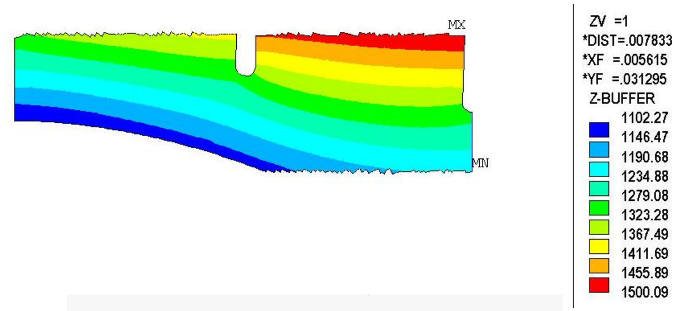
W King, “Stress-Dependence of High-Temperature Creep of Tungsten and a Tungsten-2 wt pct ThO_2 Alloy,” Met Trans, 3 (4), 1972, 941

Thermal Analysis Shows Temperatures in the 1100 – 1300 °C Range in the W Structure

- While structural temperatures are only ~0.4 T/T_m data indicates that Tungsten does creep at these temperatures.
- Power law creep model 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





$$\dot{\epsilon} = 1.3 \times 10^3 \left[e^{\frac{-53370}{T}} \right] \times \sigma^{3.53} \quad (1)$$

where

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

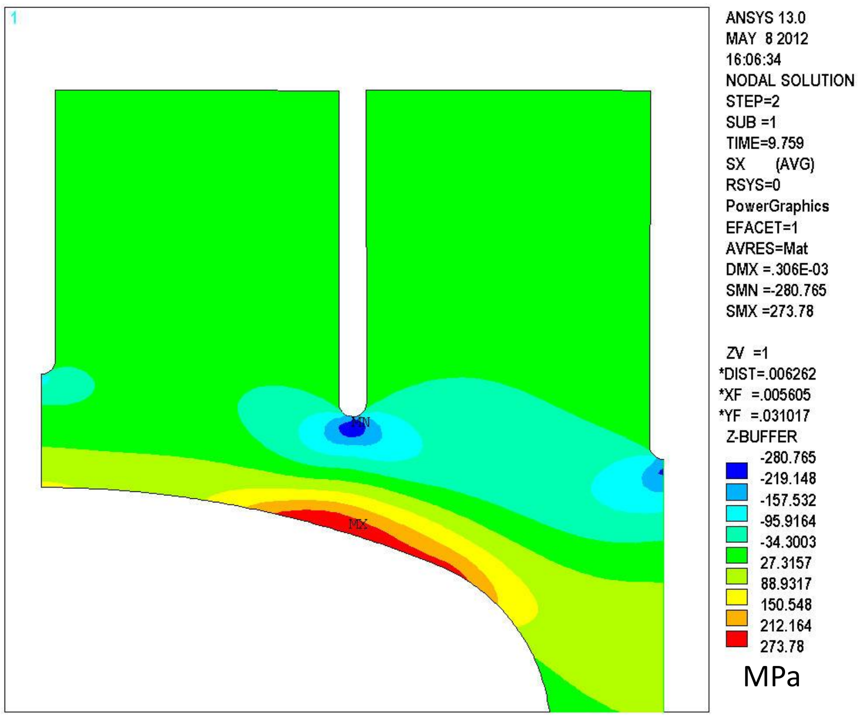
σ = creep stress, MPa, $\sigma \leq 20.0$ MPa

$1500 \leq T \leq 2900$, K

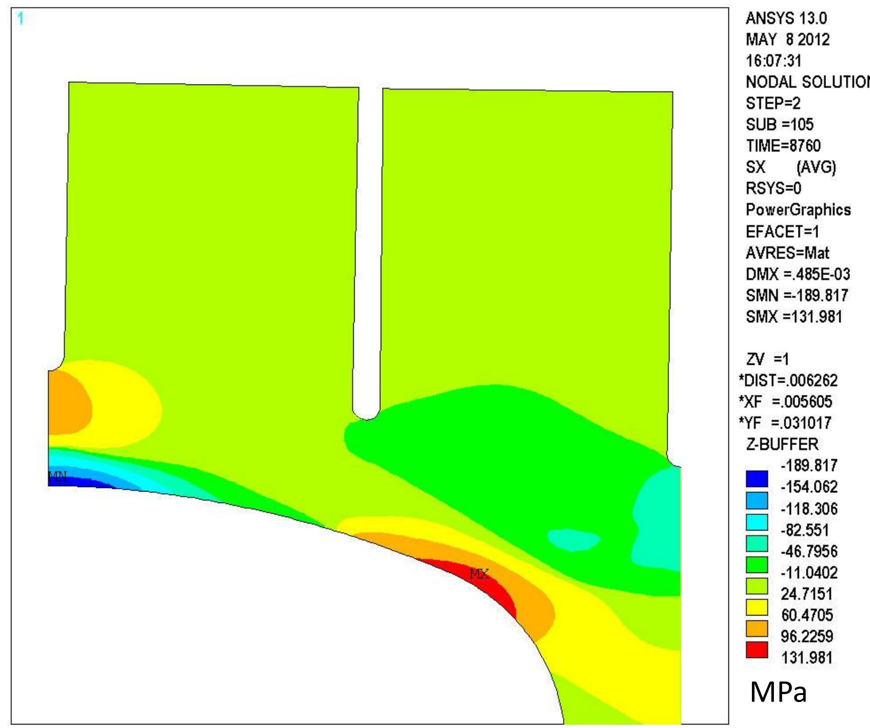
A. Purohit N. A. Hanan S. K. Bhattacharyya E. E. Gruber "Development of a steady state creep behavior model of polycrystalline tungsten for bimodal space reactor application." Argonne National Lab., IL 1995

Significant Relaxation of Thermal Stresses (Creep) Observed

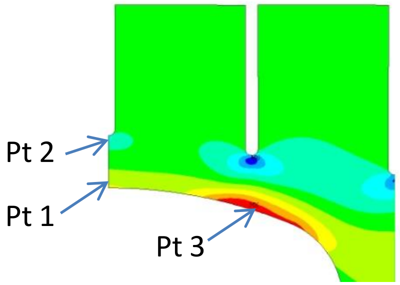
Stress at Start (Thermal + Pressure)

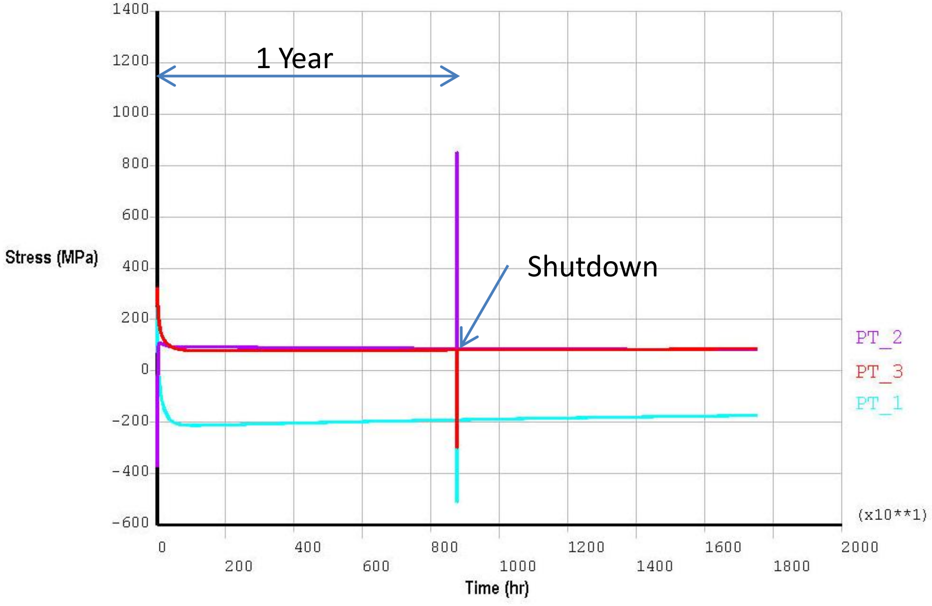


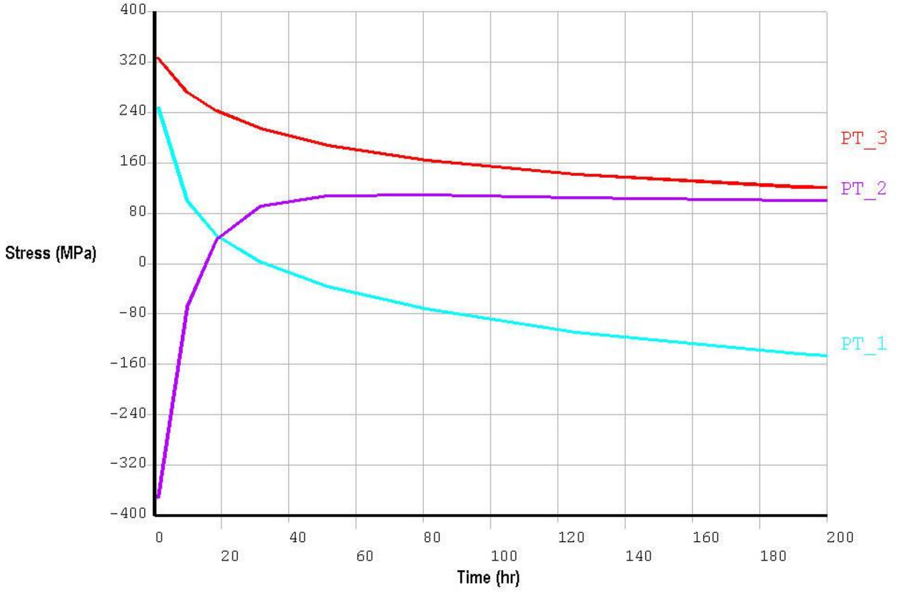
Stress After One Year



Time Histories Show Thermal Stresses are Relieved by Creep After a Few Days

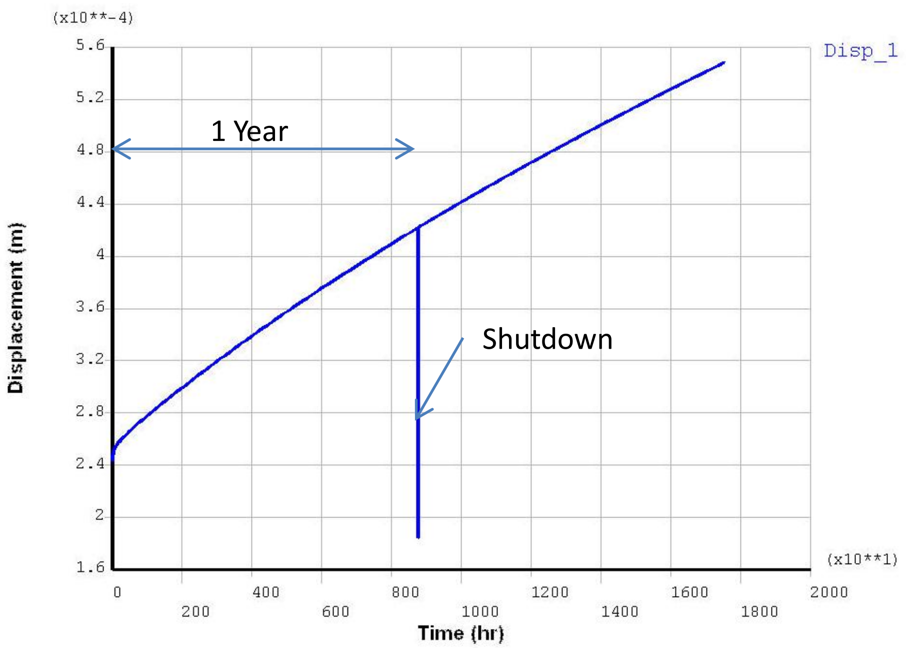




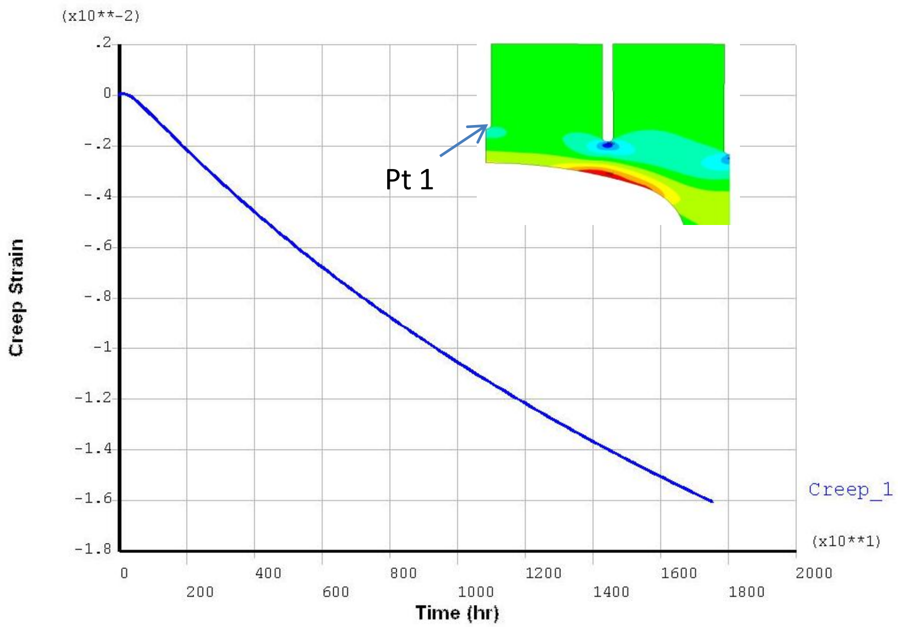


Creep Due to Pressure Stresses Continues with Time

Mid Channel Displacement

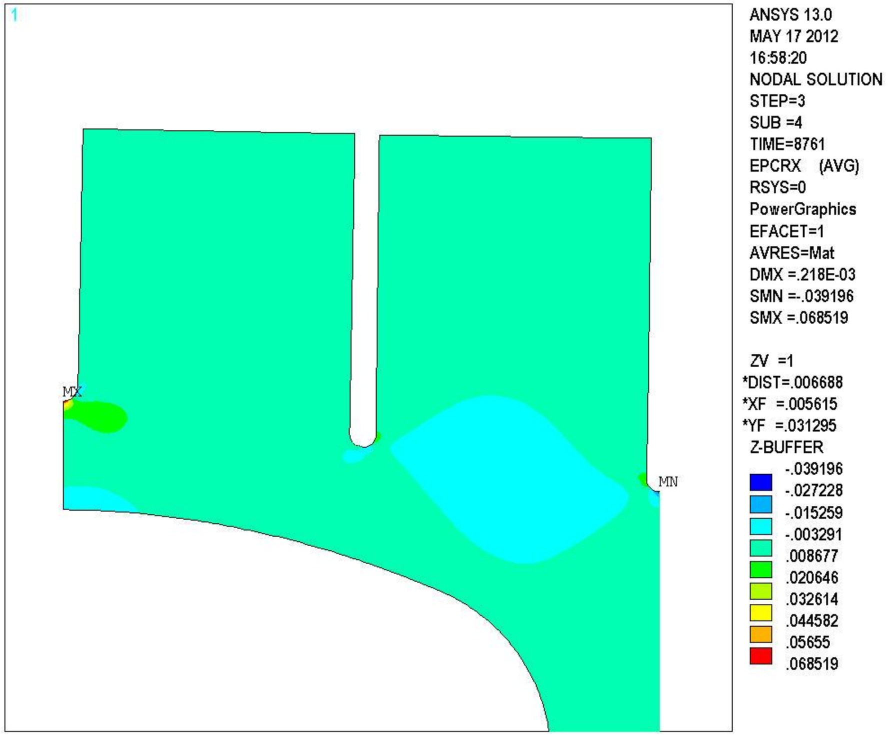


Creep Strain at Pt. 1



Creep Due to Pressure Increases with Time and Deformation Becomes Evident

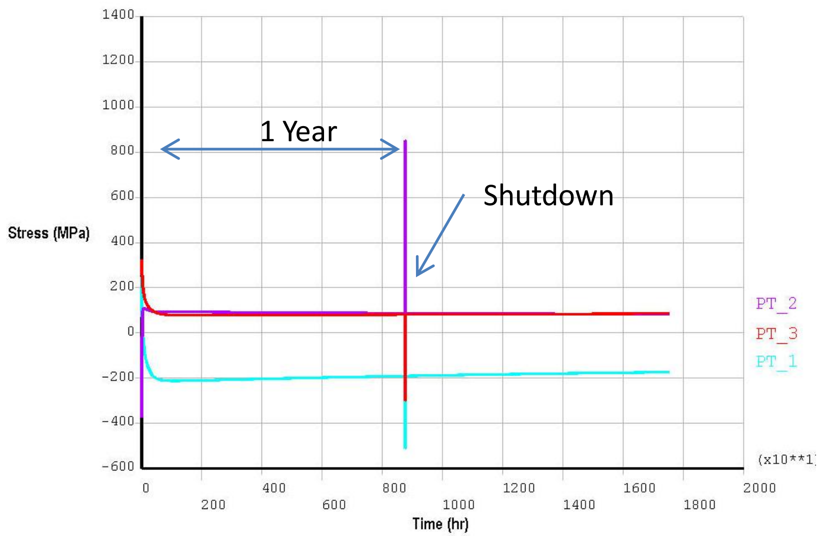
Creep After One Year

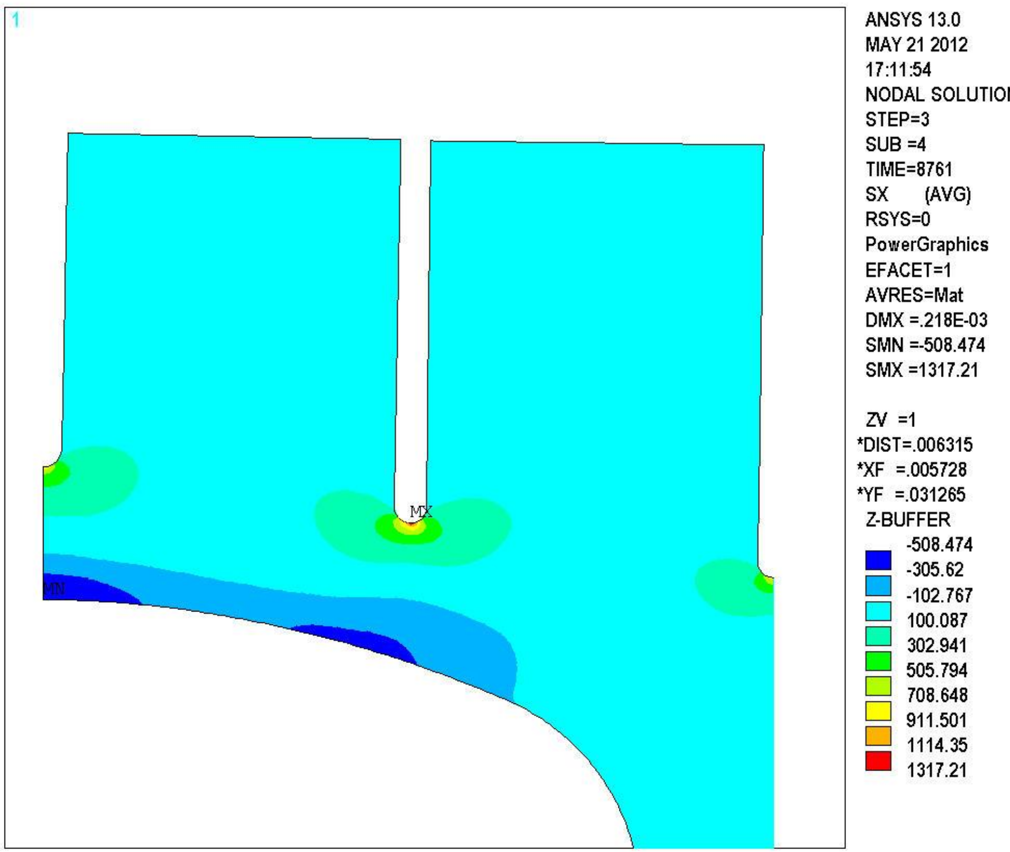


Creep After Two Years

Deformations to Scale

High Thermal Stresses When Structure Cools Down Could lead to Cracking





Assumed Creep Strain Rate May not be Applicable to this Application

- Most W creep data is for higher temperatures and lower stress
- Limited available data for temperatures/stresses of interest indicate creep behavior is different in this range

ITER is investigating W creep in this range: http://www.extremat.org/ib/site/publication/downloads/Paper%20Rieth%20No.%201951.pdf

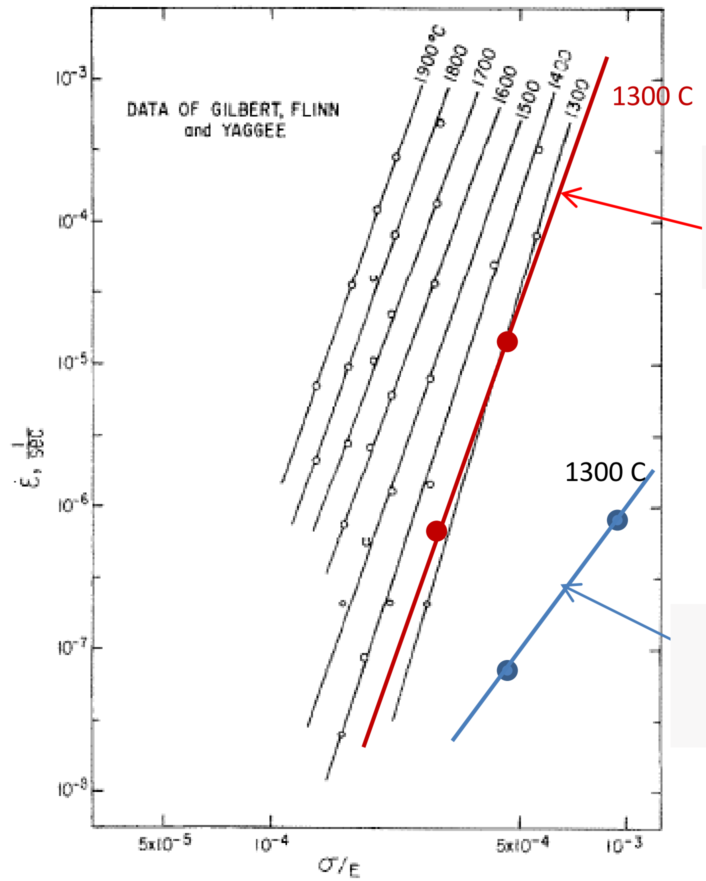


FIG. 4. Steady state creep rate of tungsten as a function of modulus corrected stress.

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

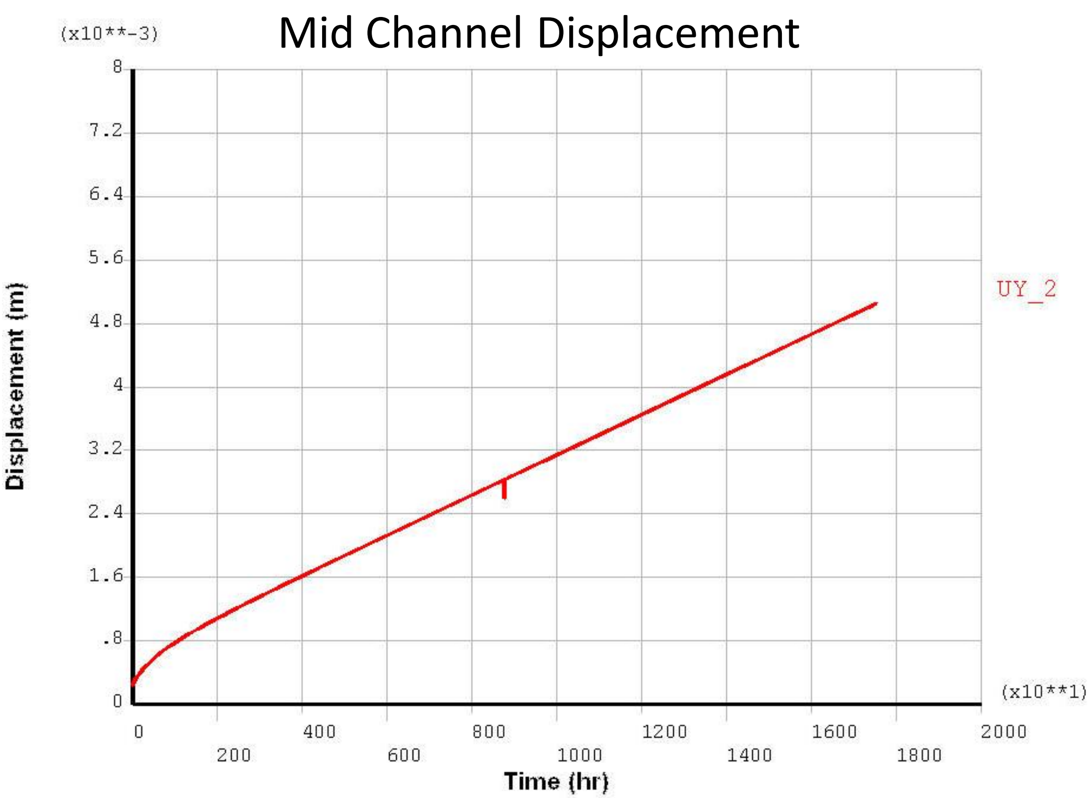
$$\dot{\epsilon} = 1.3 \times 10^{3} \left[e^{\frac{-53370}{T}} \right] \times \sigma^{3.53}$$

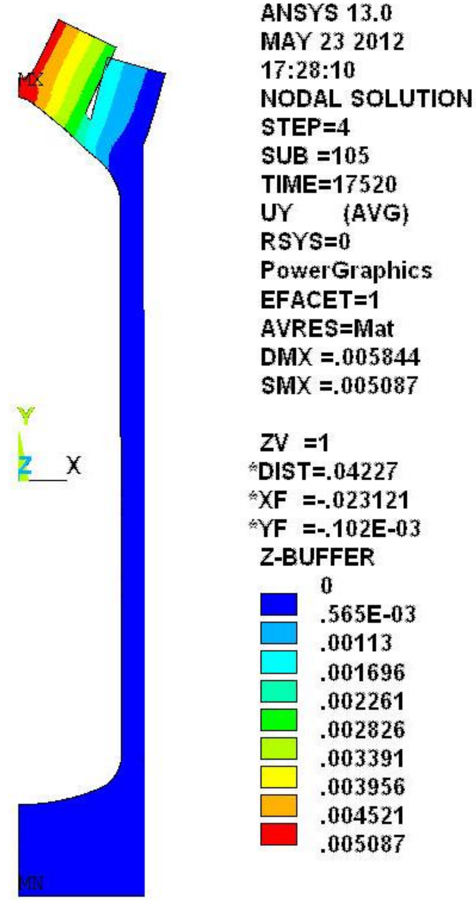
$\dot{\epsilon}$ = steady state creep rate, h^{-1}

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

$1500 \leq T \leq 2900$, K

Using Data Fit from Previous Page Produces Excessive Creep Deformation





Conclusions

- The problem is primary stresses from coolant pressure
- Thermal stresses are relaxed out
- Relaxation could cause problems at shutdown
- Creep rates are strong functions of stress and temperature, so relatively small changes can have dramatic effects

Next Steps

- Verify creep data
- Explore:
  - Lower coolant pressure
  - Thicker walls
  - Lower temperatures
- We may need to employ a tungsten alloy with enhanced creep strength

Seismic Analysis for ITER

- References
  - Masataka Nakahira et al, "Design and Validation Test of Seismic Isolation for ITER," 7th Int Conf Nuc Eng, Tokyo, April 1999.
  - "Tokamak Seismic Analysis," Chapter 2.15, ITER G A0 FDR 1 01-07-13 R1.0.
  - Sorin, Barabaschi, and Sannazzaro, "Seismic Analysis of ITER Tokamak Including Interaction with Soil and Building, Fus Eng Des, 69, 2003, 611-615.
  - http://www.iter.org/newsline/65/183

Background

- ITER site is considered to be low to medium seismic area (6.2 quake in 1909, centered nearby)
- Reference ITER design considers horizontal and vertical accelerations up to 0.2g.
- Analysis employs response spectrum method, with "loads" applied at anchor points.
- Soil interaction is neglected.
- 5% damping is used in most cases

Design Response Spectra

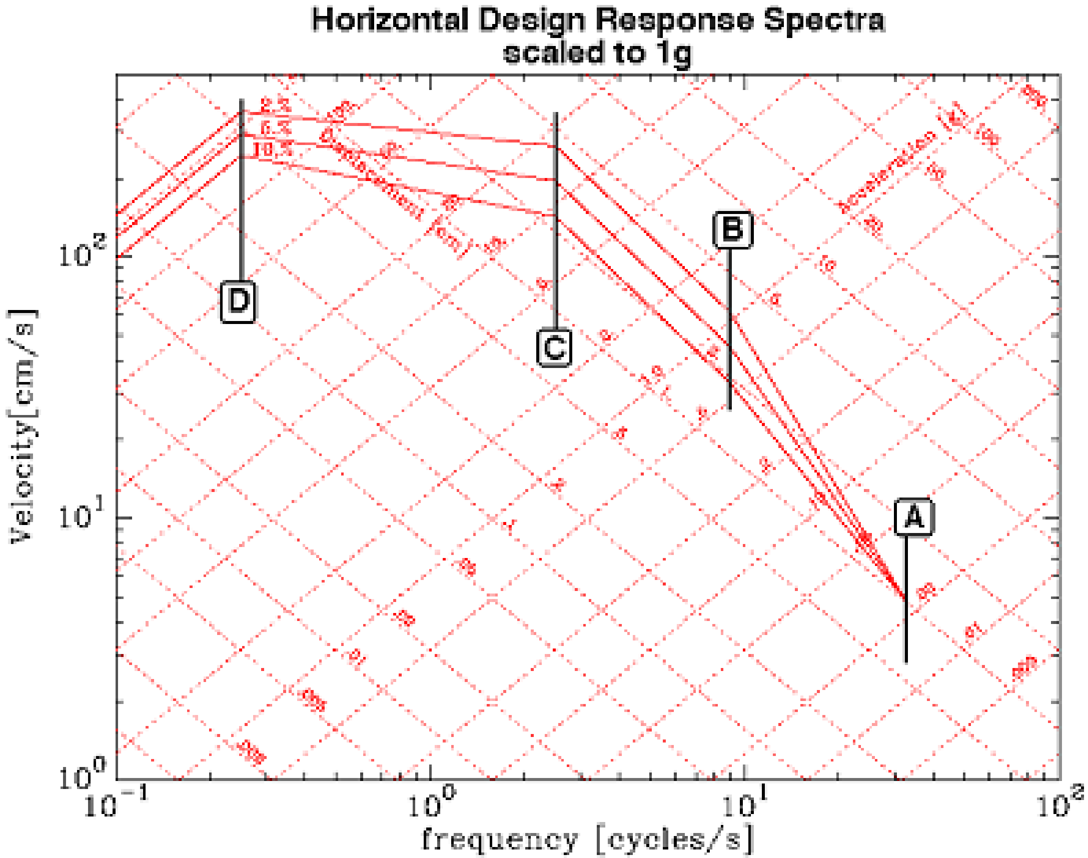


Figure 2.15.2-1 Horizontal Ground Acceleration DRS Scaled to 1 g at point A. The points A, B, C, D are reference frequencies defined in the NRC guides.

Model

- 3-D FEM with beams and shells
- 20 degree sector (vertical motion) and 90 degree sector (horizontal – symmetric and antisymmetric)

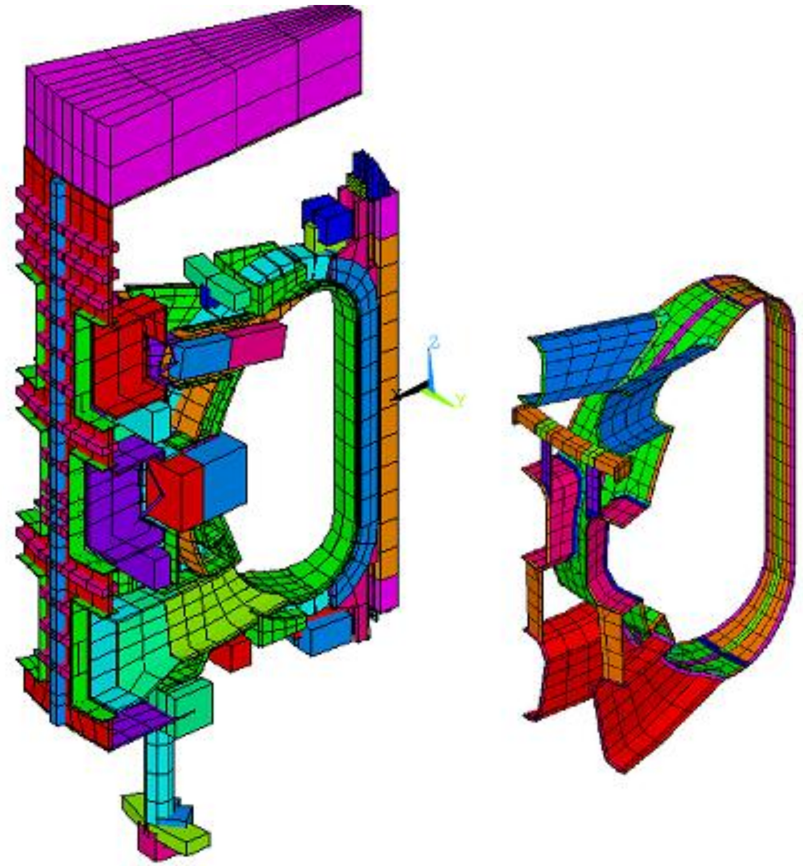


Figure 2.15.3-1 Finite Element Model Used for the DRS Seismic Analysis of ITER FEAT. Thermal Shield Model Shown on the Right Side.

180 degree model

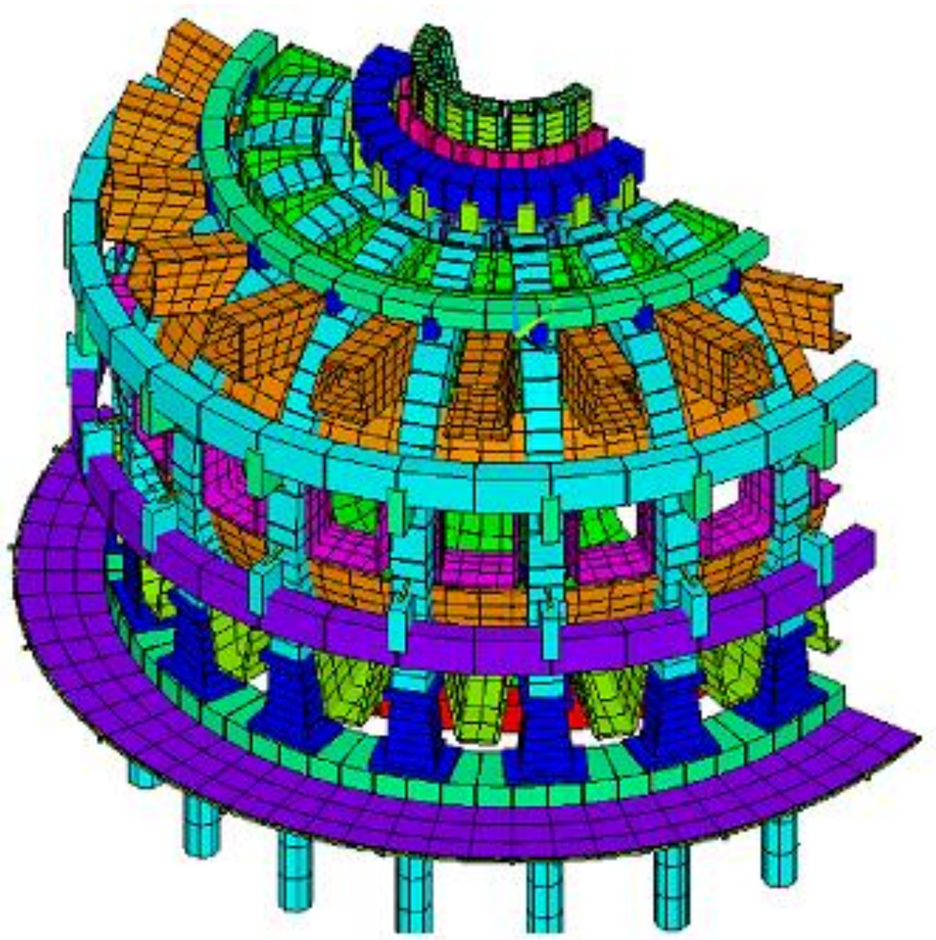


Figure 2.15.3-2 Seismic Model of the Tokamak Extended to 9 Sectors.

Natural Frequencies

Table 2.15.4-1 First Four Eigenvalues for Both Vertical and Horizontal Excitation of the Tokamak.

	Horizontal excitation	Vertical excitation
1 Frequency	2.82 Hz	8.10 Hz
2 Frequency	3.40 Hz	8.54 Hz
3 Frequency	5.37 Hz	9.90 Hz
4 Frequency	6.56 Hz	11.2 Hz

- Mode 1 – entire machine rocks
- 2 – cryostat horizontal translation/rocking
- 3 & 4 – horizontal oscillation of thermal shield and vacuum vessel with respect to magnets

Displacements

Table 2.15.4-2 Relative Displacements Obtained in the SL-2 Seismic Analysis.

Name	Radial mutual displac. mm	Vertical mutual displac. mm
VV – TFC, equatorial inboard	6.7	2.5
VV – TFC, top	7.4	2.0
VV – TFC, equatorial outboard	6.9	2.2
CS – TFC, equatorial inboard	1.4	0.7
TS – TFC, equatorial inboard	6.6	1.1
TS – VV, equatorial inboard	1.8	2.8

Reaction Loads

Table 2.15.4-3 Absolute Values of the Reaction Loads in the Main Machine Supports

	Triaxial Earthquake	Dead Weight	Triaxial and Dead Weight
Gravity Supports Response:			
Axial load, MN	7.8	-10.9	18.6
Toroidal load, MN	12.4	0	12.4
Radial moment (top), MNm	7.64	0	7.6
Radial moment (bottom), MNm	35.4	0	35
Toroidal moment, MNm	0.44	-0.7	1.1
Axial (torsion) moment, MNm	3.0	0	3.
VV Supports Response:			
Axial load, MN	4.6	-6.4	11.1
Toroidal load, MN	9.1	0	9.1
Radial moment, MNm	9.1	0	9.1
Toroidal moment, MNm	0.2	0.11	0.3

Conclusion

- ITER design meets 0.2 g specification without isolation
- However, isolation will be employed

Seismic Isolation System

- Machine will be on 560 pads (elastomer and steel)
- Tokamak building, diagnostic building, tritium building also isolated
- Pads are 90x90x20 cm on 1.8 m tall concrete columns

6-month plan

- Finish Thermal Creep Analysis (verify data, design changes/parametrics)
- Complete analysis of magnet quench with ferromagnetic internal components

12-month plan

- In addition to thermal creep analysis, progress can be made on disruption analyses