Wall Response for Laser IFE Chambers

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Workshop Agenda

Outline

- Analytical Stress Models
- Finite Element Results
  - Thermal
  - Fatigue
  - Fracture
- Conclusions

Why are Stresses Important?

- Stresses contribute to:
  - Yielding
  - Fracture/fatigue
  - Creep/swelling
  - Ratcheting
  - Roughening
  - Spalling
- We must understand stresses to understand these phenomena

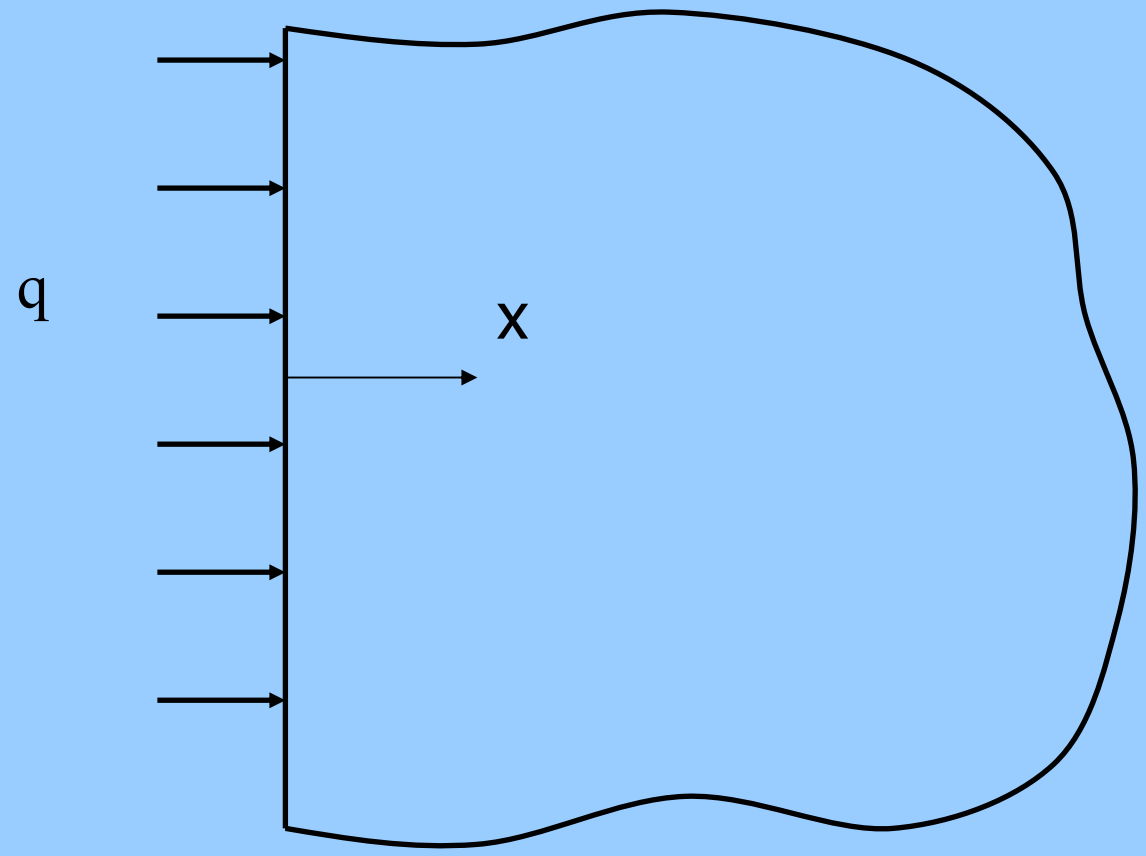
We must consider…

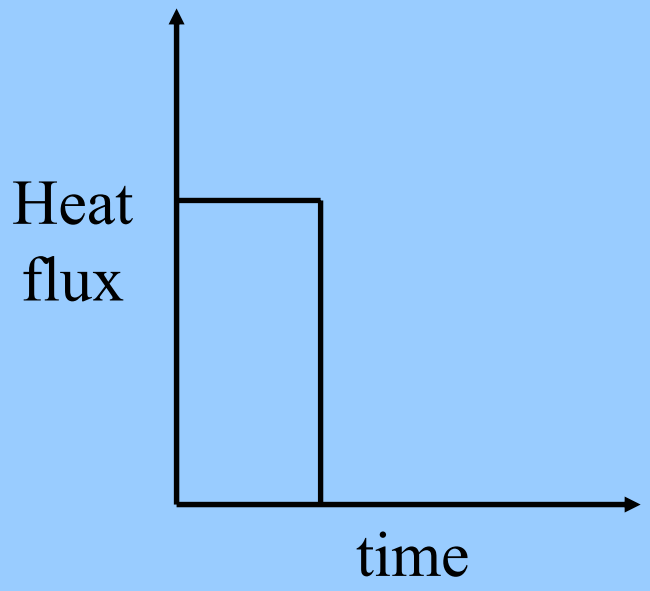
- Detailed heating
  - Volumetric deposition
  - Spatial and temporal variation on surface
- Inertial Effects
- Thermal Waves
- Geometry
- Fatigue, Fracture, Plasticity
- For short pulses, some of these effects can often be ignored

Baseline Model

- Assume:
  - 1-D temperature distribution
  - Surface heating
  - Short pulse
  - No inertial effects
  - No thermal waves
  - Full constraint in 2 dimensions, no constraint in third dimension

Schematic





Baseline Model

$$\sigma_{yy} = \sigma_{zz} = \frac{-E\alpha T}{1-\nu}$$

$$\sigma_{xx} = 0$$

$$T_s = \frac{2q}{k}\sqrt{\frac{\kappa t}{\pi}}$$

$$\sigma_{yy} = \sigma_{zz} = \frac{-2qE\alpha}{(1-\nu)k}\sqrt{\frac{\kappa t}{\pi}}$$

E=elastic modulus

α=thermal expansion coefficient

κ=thermal diffusivity

k=thermal conductivity

ν=Poisson's ratio

q=surface heat flux

t=pulse width

T=temperature change from stress-free temperature

Volumetric Heating

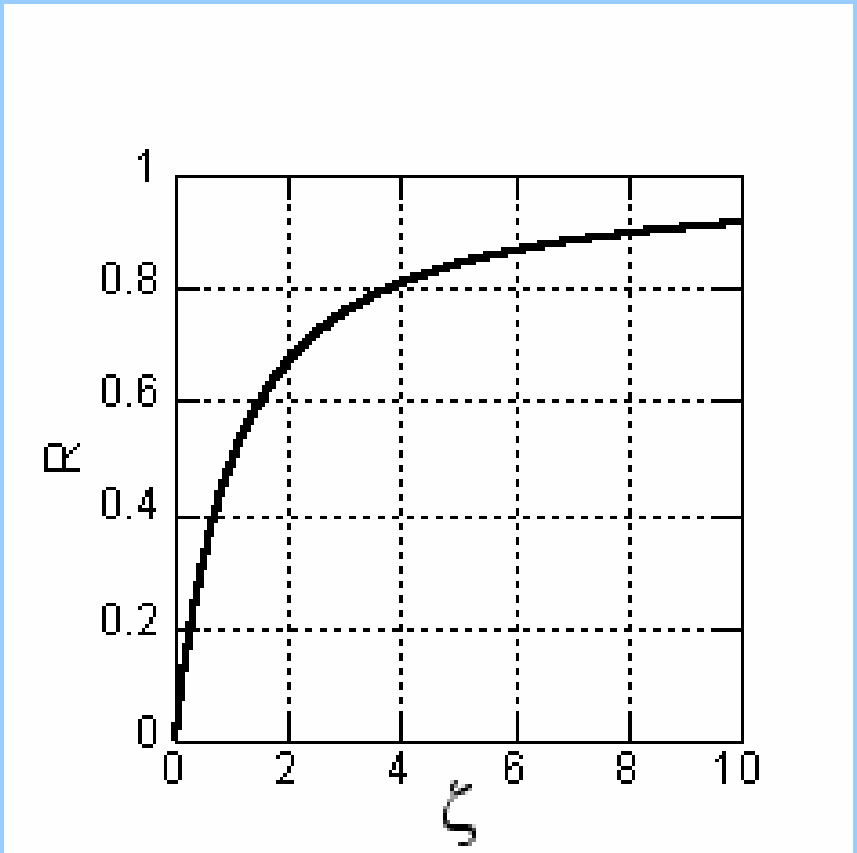
Energy deposition falls off exponentially

$$Q''' = Ae^{-\gamma x}$$

$$T_{surface} = \frac{q}{k\gamma}\left[\frac{2\zeta}{\sqrt{\pi}} - 1 + e^{\zeta^2} erfc(\zeta)\right]$$

$$\zeta = \gamma\sqrt{\kappa t}$$

Temperature Normalized to Result from Surface Heating



$$\zeta = \gamma\sqrt{\kappa t}$$

For long times, the volumetric heating is inconsequential

Interpretation

- Dimensionless parameter here is ratio of characteristic deposition length to diffusion length
- When this is large, the heating can be assumed to be surface heat
- In tungsten for a 10 ns pulse, the e-folding of the deposition must be more than 90 nm for a 10% effect and more than 12 nm for a 1% effect

Modified Model

$$Q''' = Ae^{-\gamma x}$$

$$\zeta = \gamma\sqrt{\kappa t}$$

$$T_{surface} = \frac{q}{k\gamma}\left[\frac{2\zeta}{\sqrt{\pi}} - 1 + e^{\zeta^2} erfc(\zeta)\right]$$

$$\sigma_{yy} = \sigma_{zz} = \frac{-2qE\alpha}{(1-\nu)k\gamma}\left[\frac{2\zeta}{\sqrt{\pi}} - 1 + e^{\zeta^2} erfc(\zeta)\right]$$

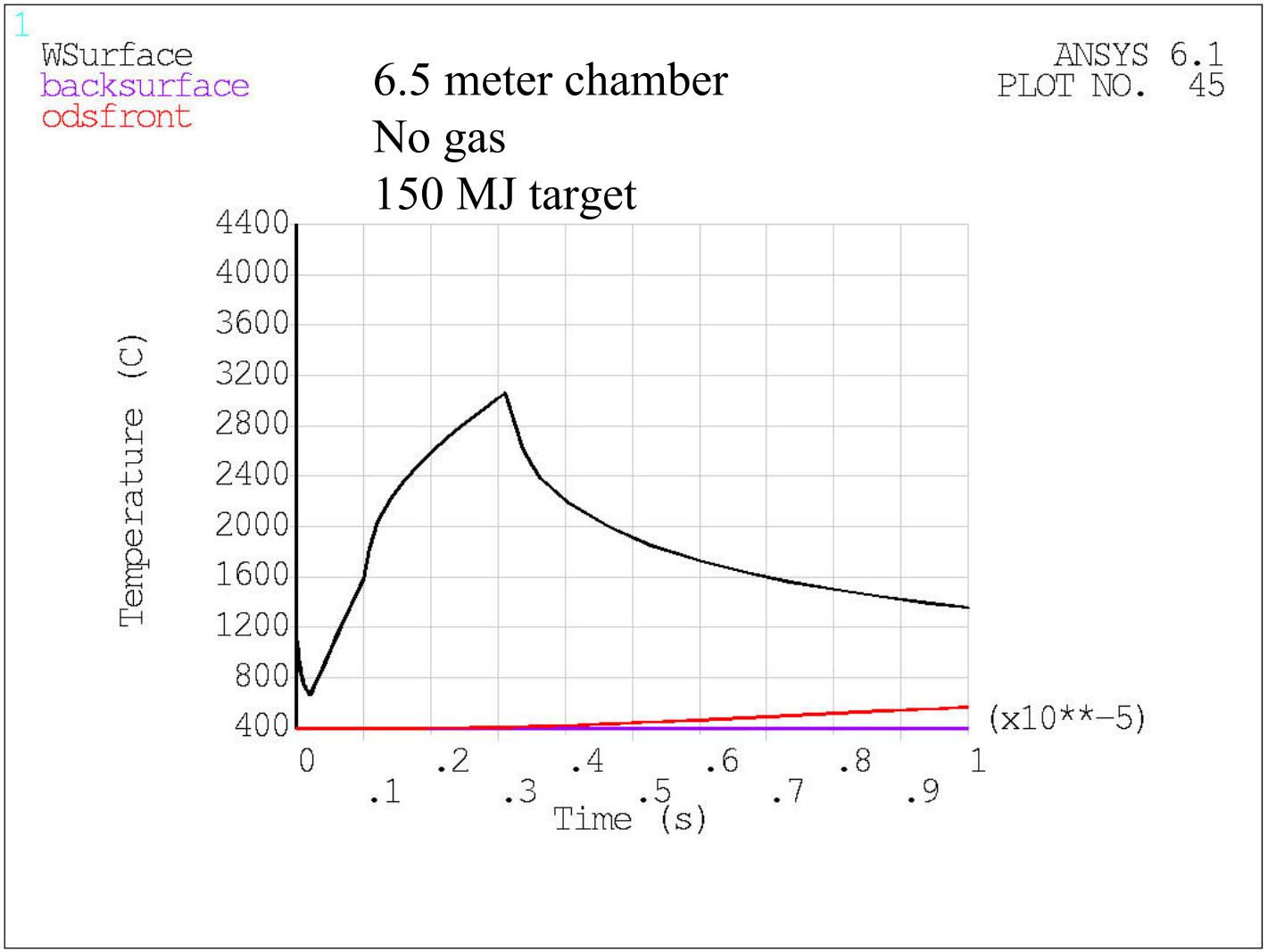
Calculations for HAPL

- HAPL = high average power laser
- http://www-ferp.ucsd.edu/HAPL/
- Calculations which follow address design of the chamber wall for this project
- Many fundamental design parameters still not identified

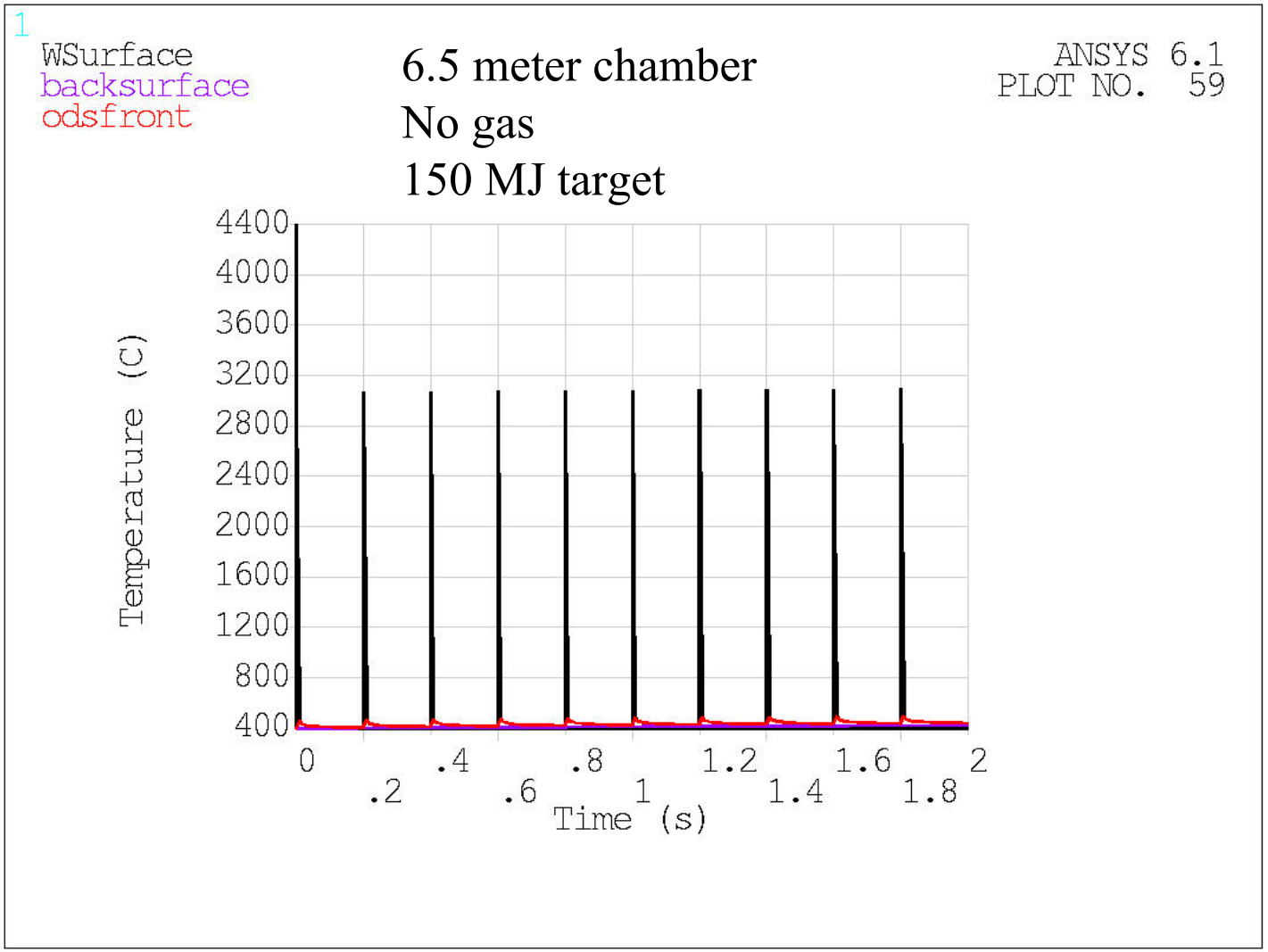
Wall Design

- Chamber wall is tungsten coating on a steel wall
- Coating thickness is approximately 100 microns
- Steel will likely be ODS ferritic
- Carbon walls are also under consideration

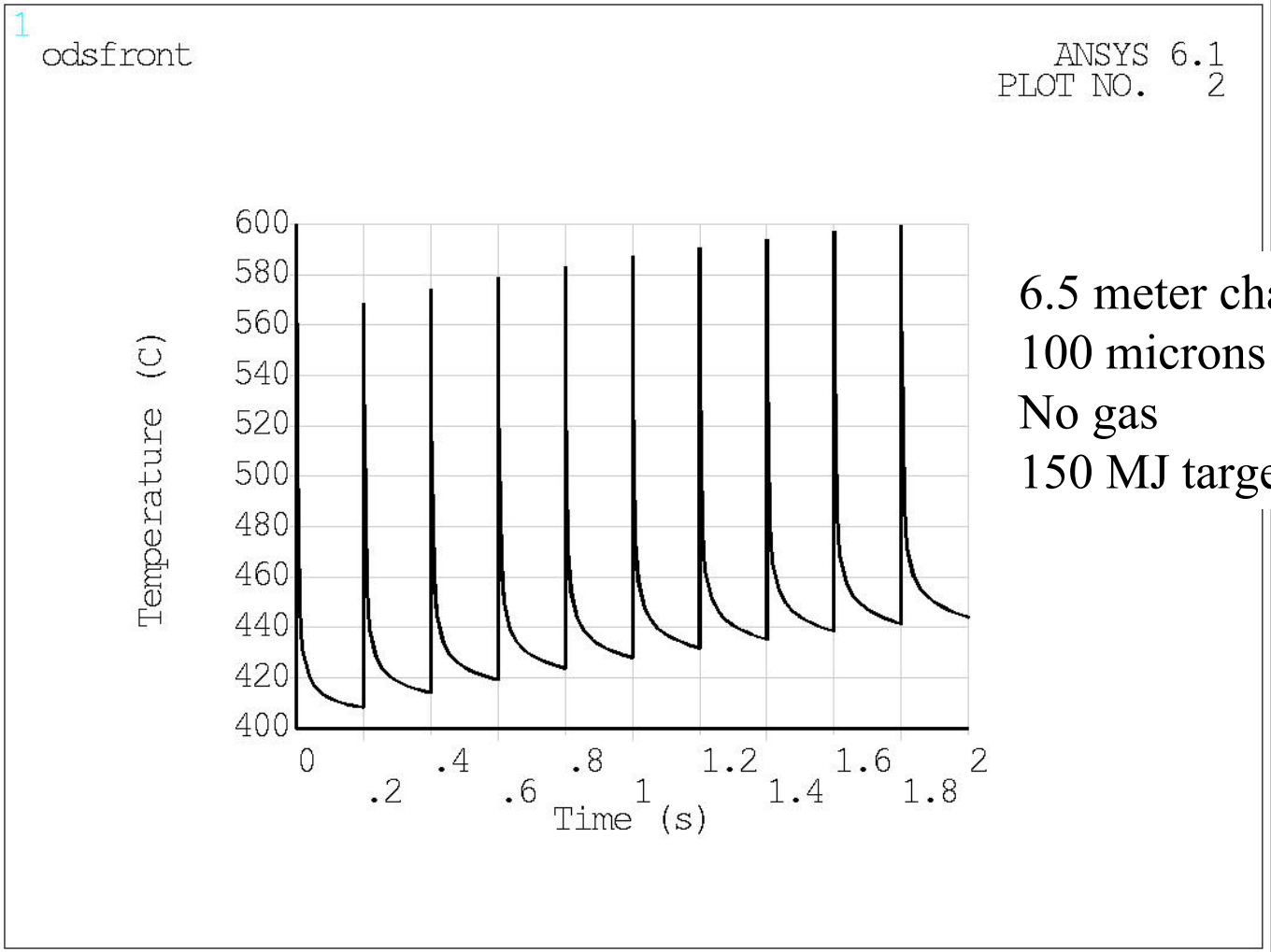
Temperature Histories - first cycle



Temperature Histories – 10 cycles

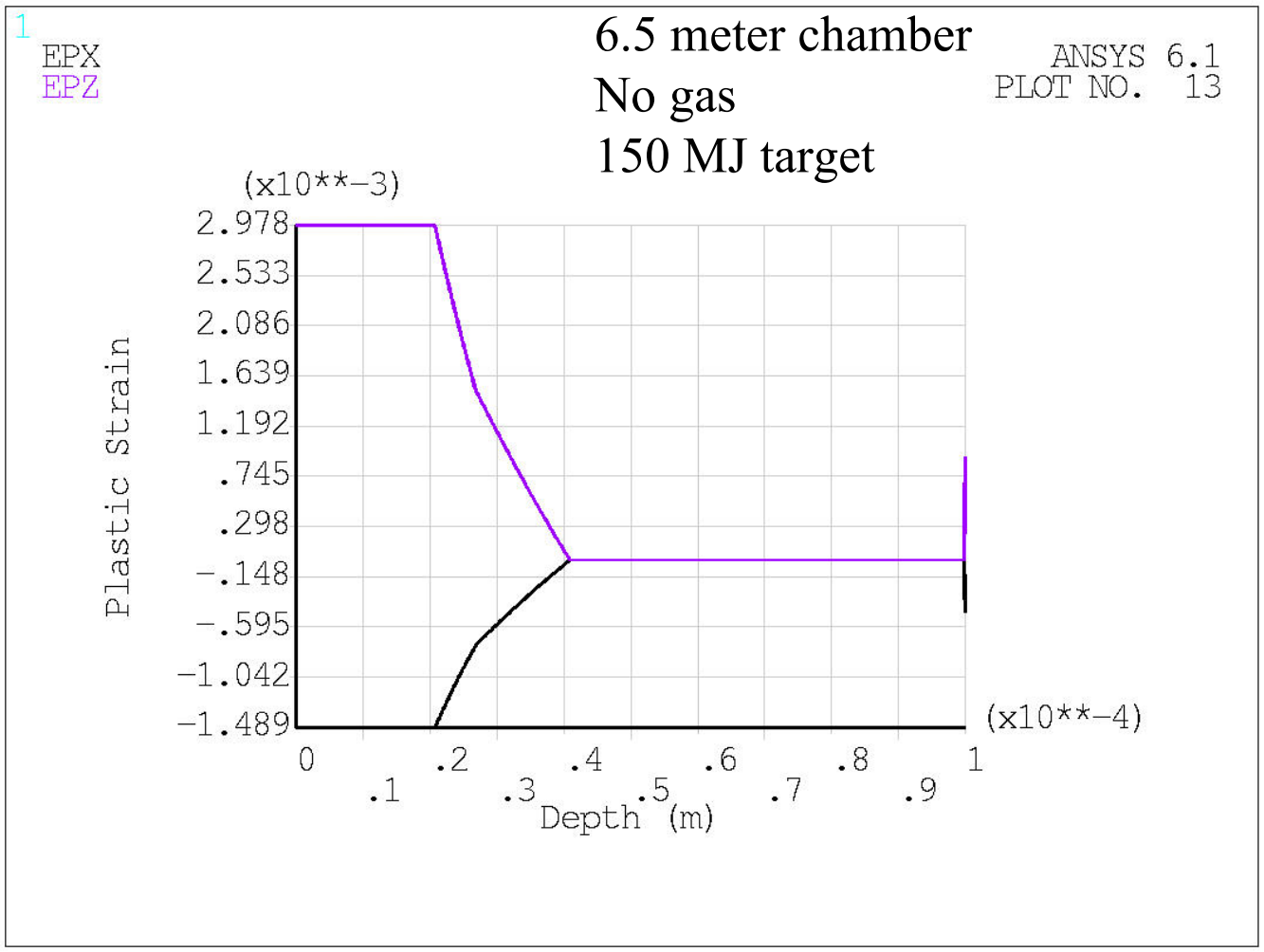


Temperature History at Surface of Steel

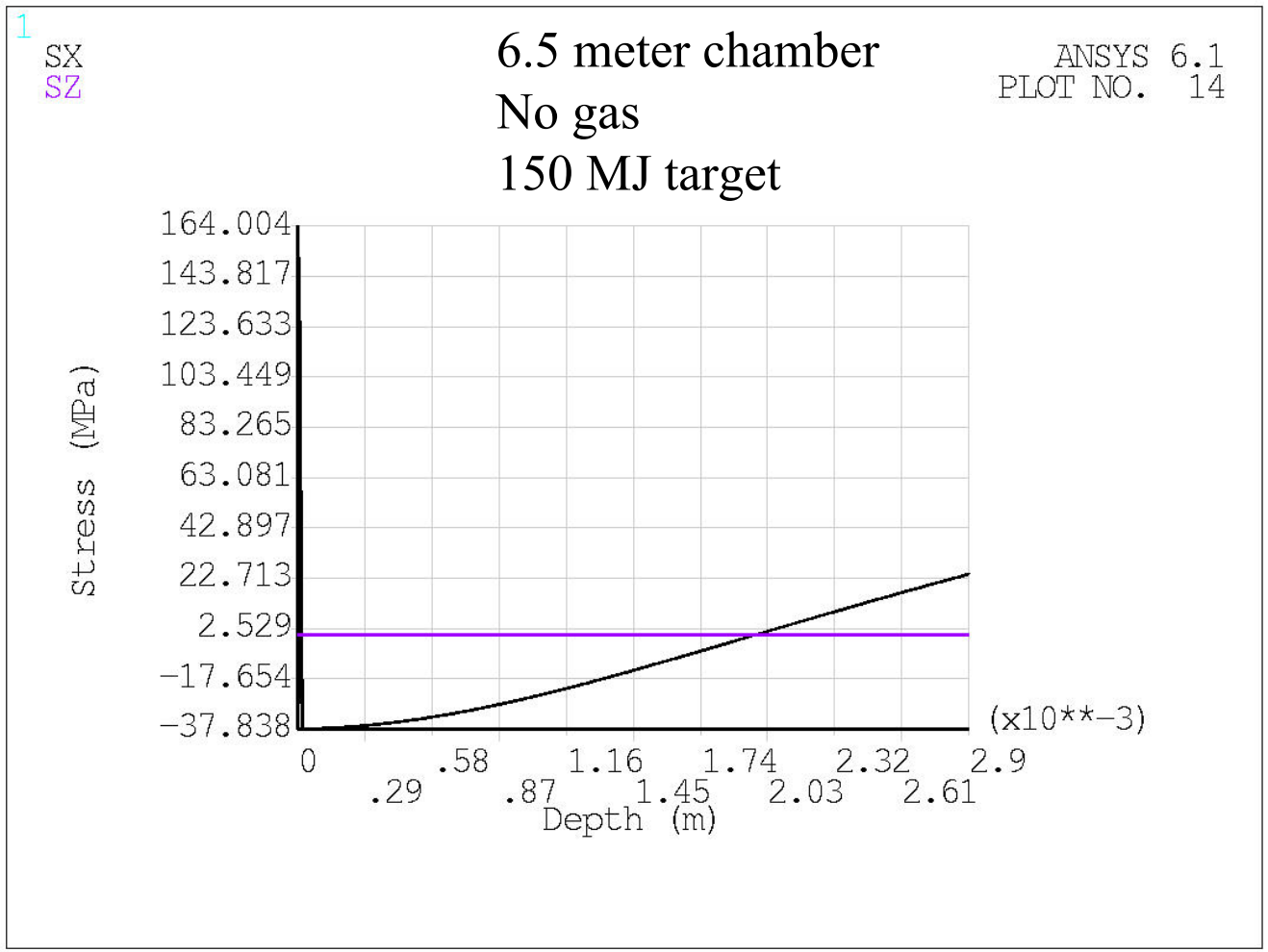


6.5 meter chamber
100 microns W
No gas
150 MJ target

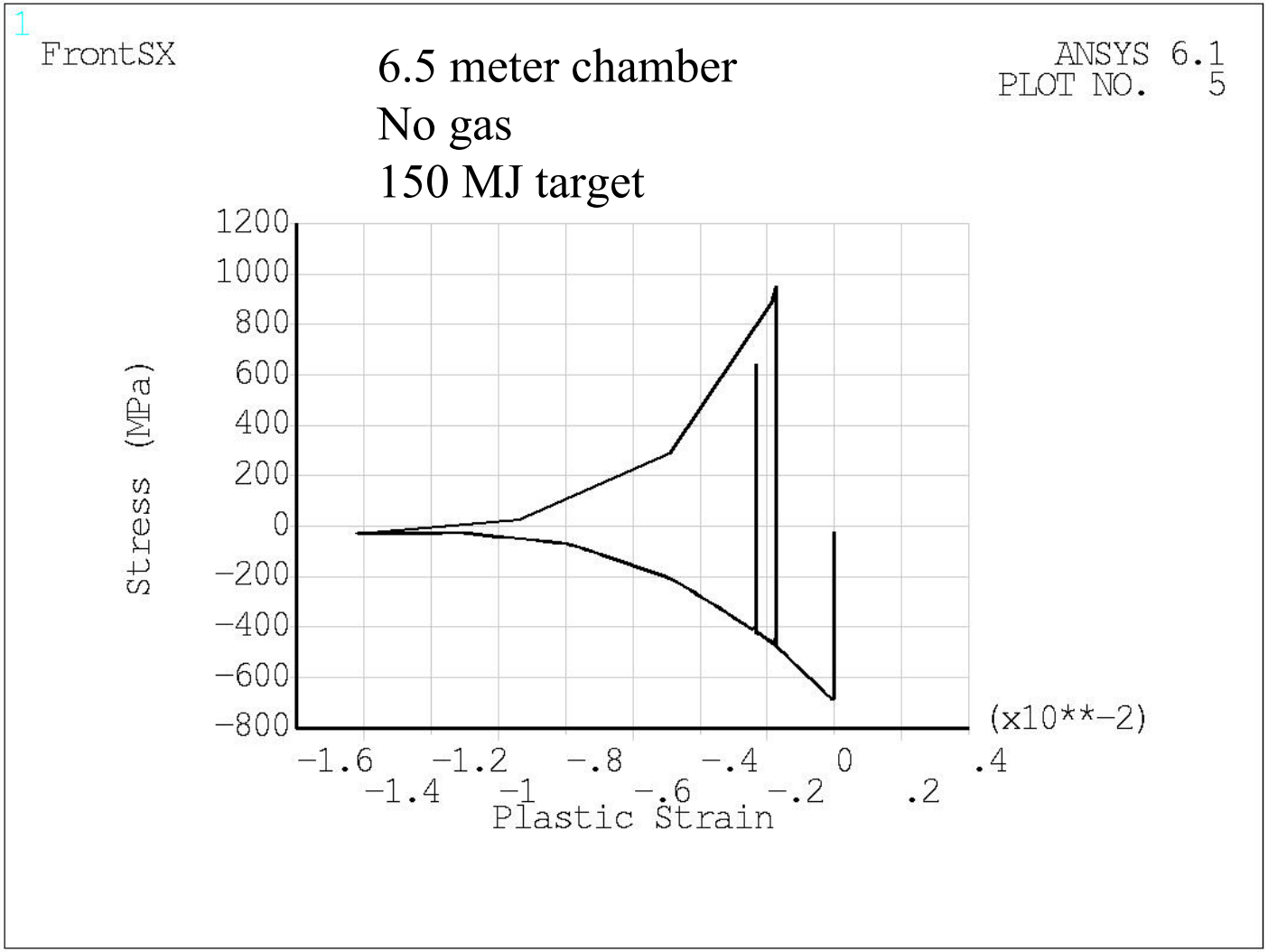
Strain Distributions – Tungsten after last pulse



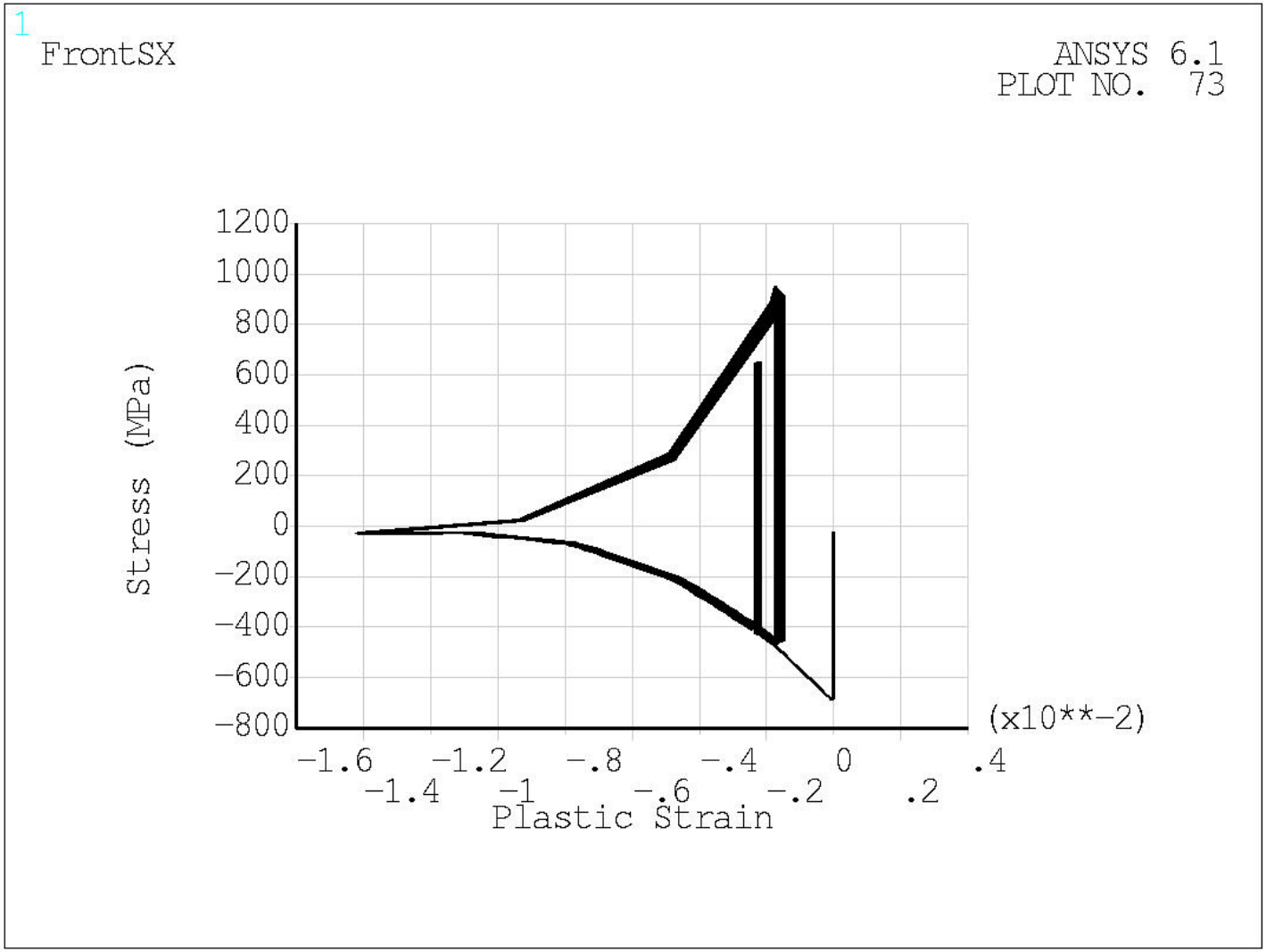
Stress Distributions – Steel after last pulse



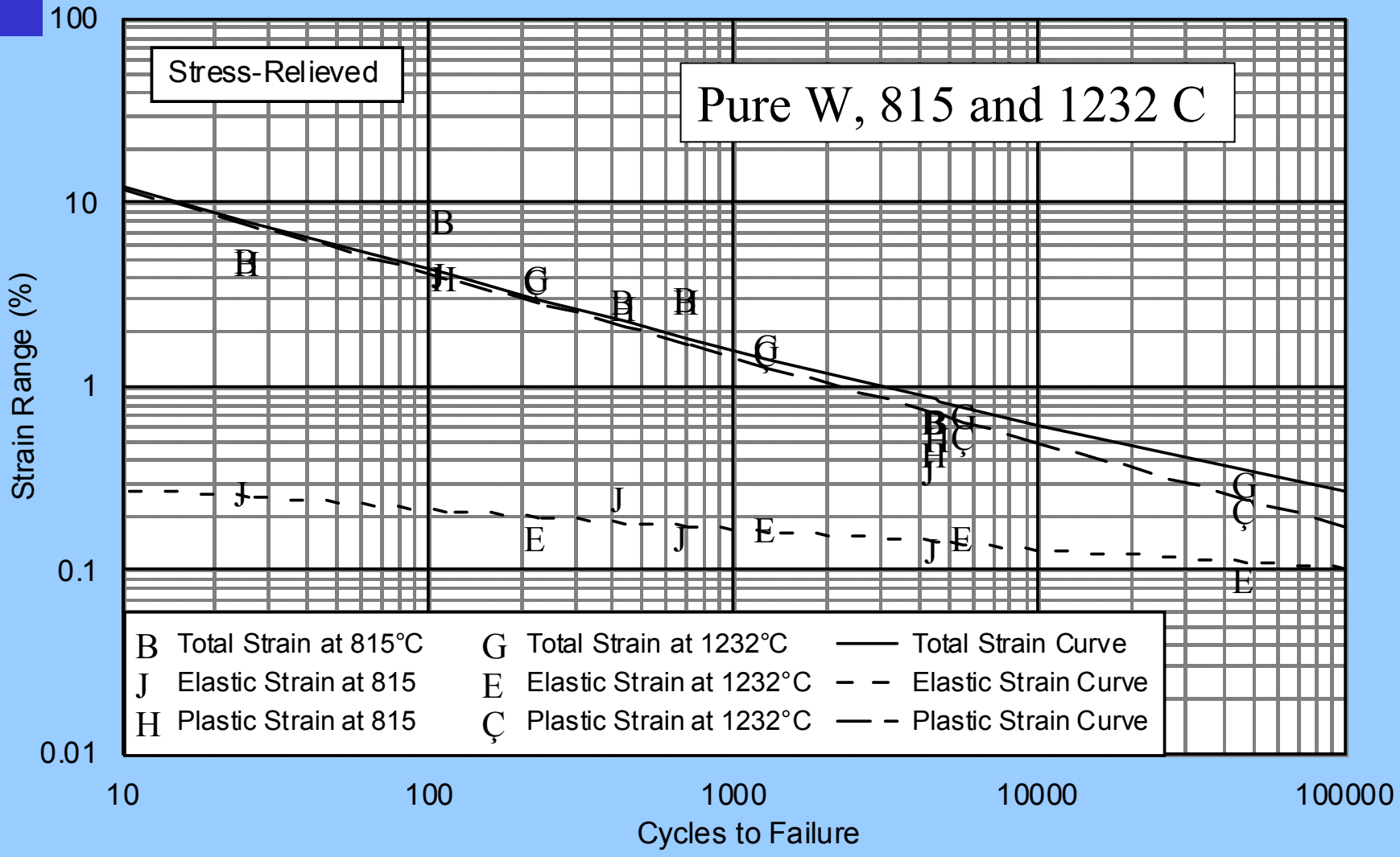
Stress-Strain Behavior at W Surface 1 Cycle



Stress-Strain History at W Surface 10 cycles Superimposed



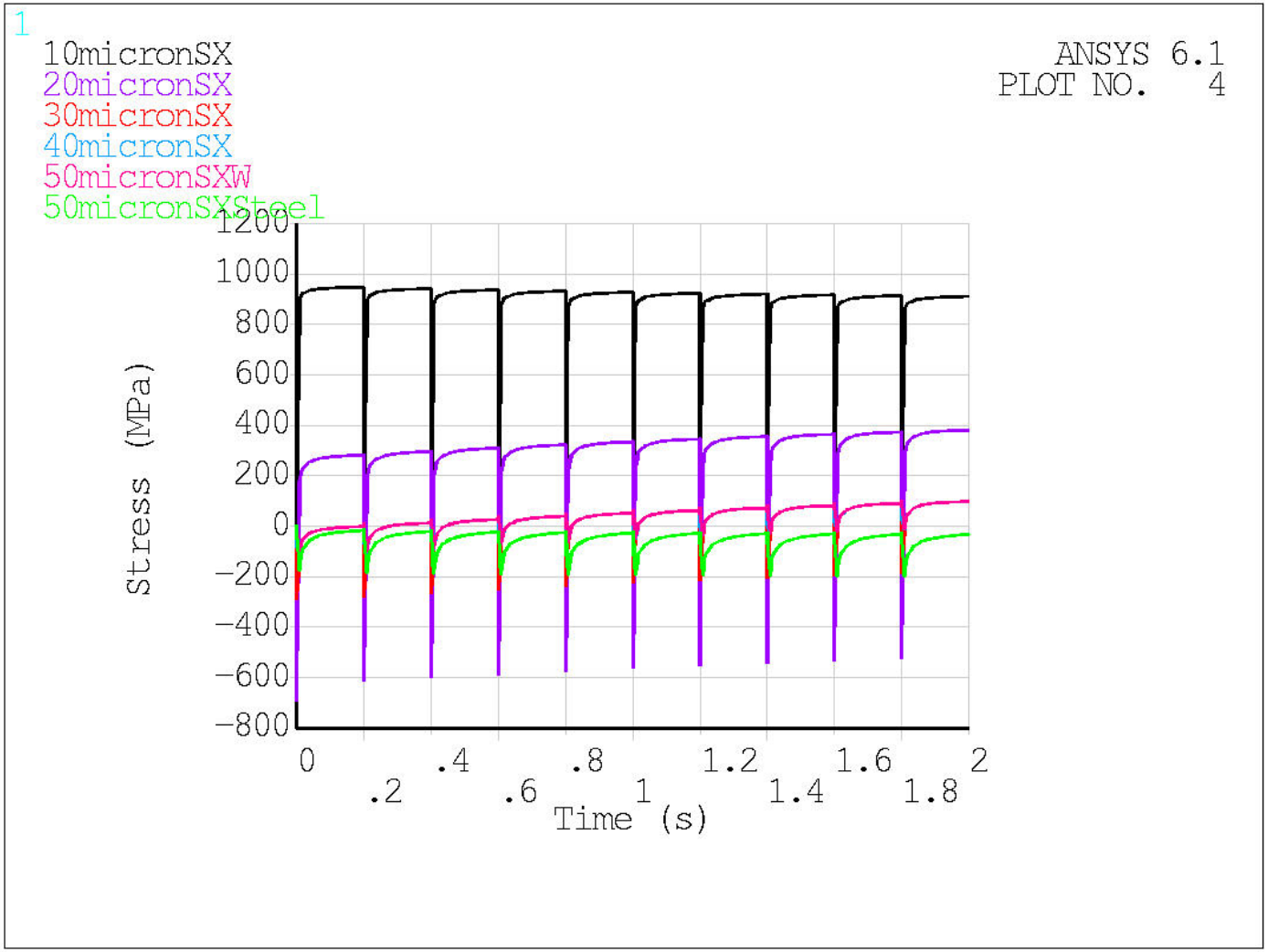
Fatigue Data for Stress-Relieved Tungsten



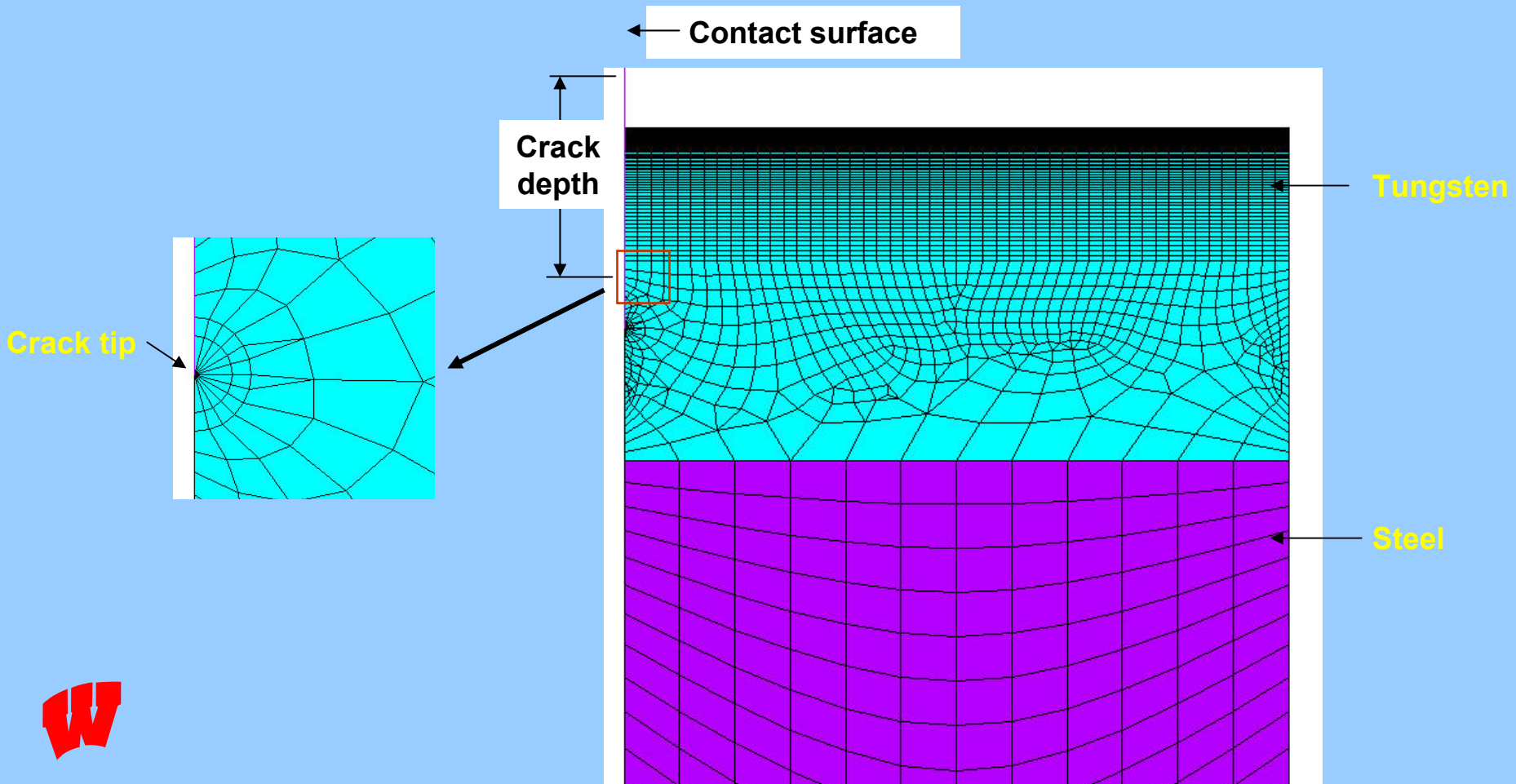
Fatigue Analysis

Chamber Radius (m)	Xe Pressure (mTorr)	Multiaxial Strain Range (%)	Cycles to Cracking
6.5	0	2.4	300
7.5	0	1.6	1000
5.5	10	3.0	200
6.5	10	2.0	500
7.5	10	0.8	3000
7.5	20	0.7	4000
6.5 (40 MJ target)	0	0.13	$>10^5$

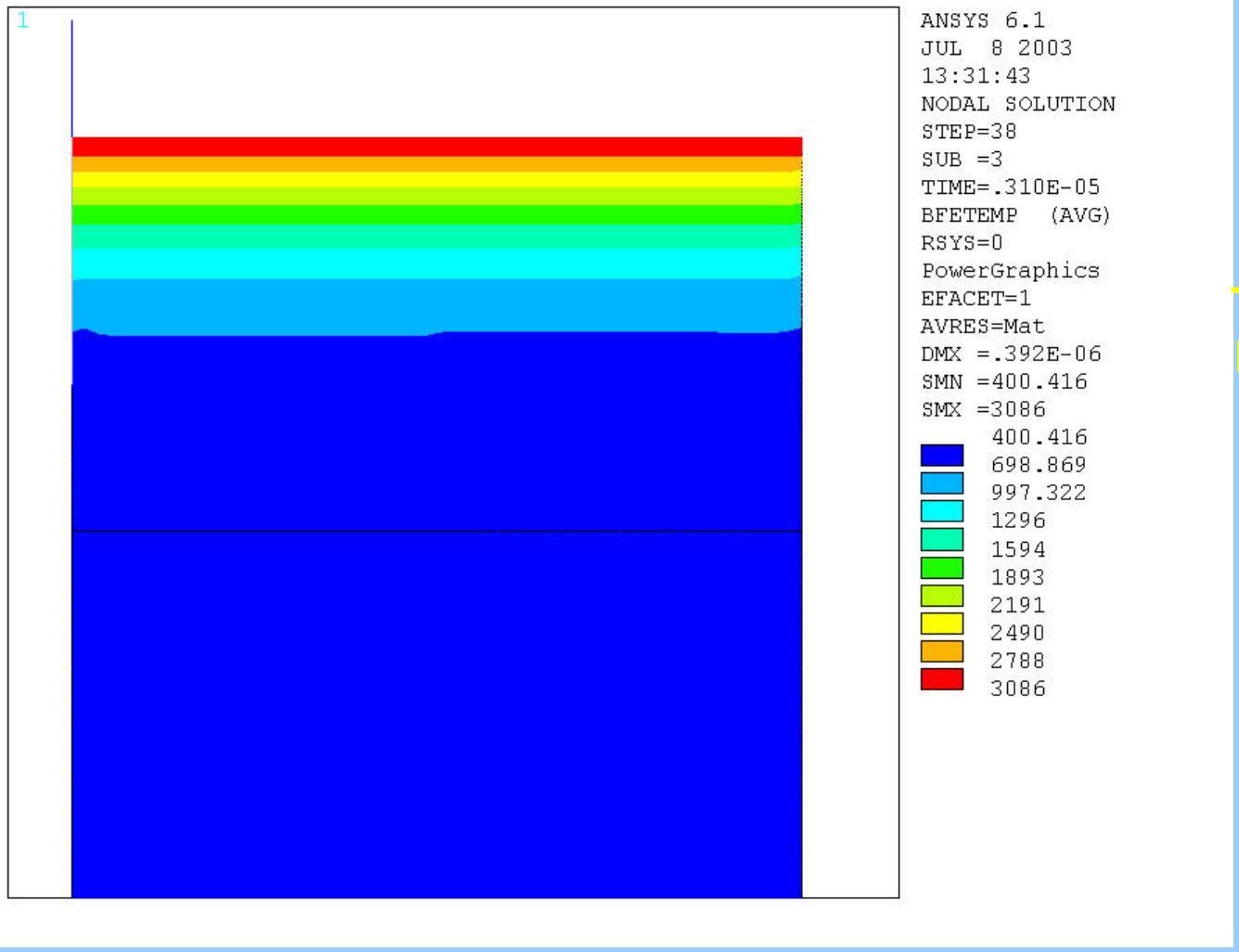
Crack Growth Through Thickness is Governed by Stress Gradients



Fracture Mechanics Analysis of Tungsten Coating



Thermal Response of Structure

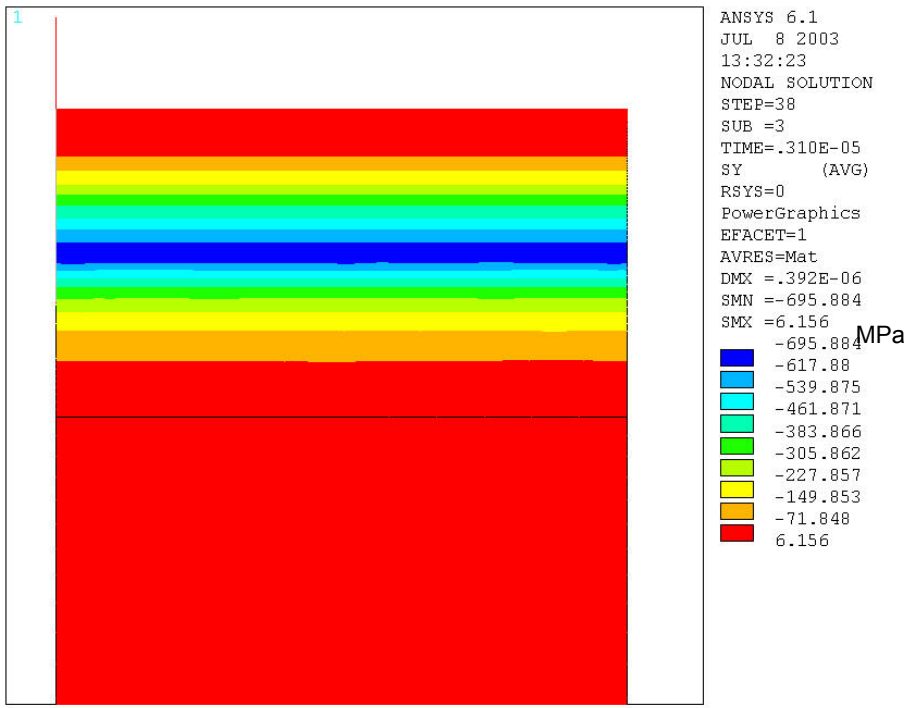


Temperature Contours Near Surface at end of Pulse

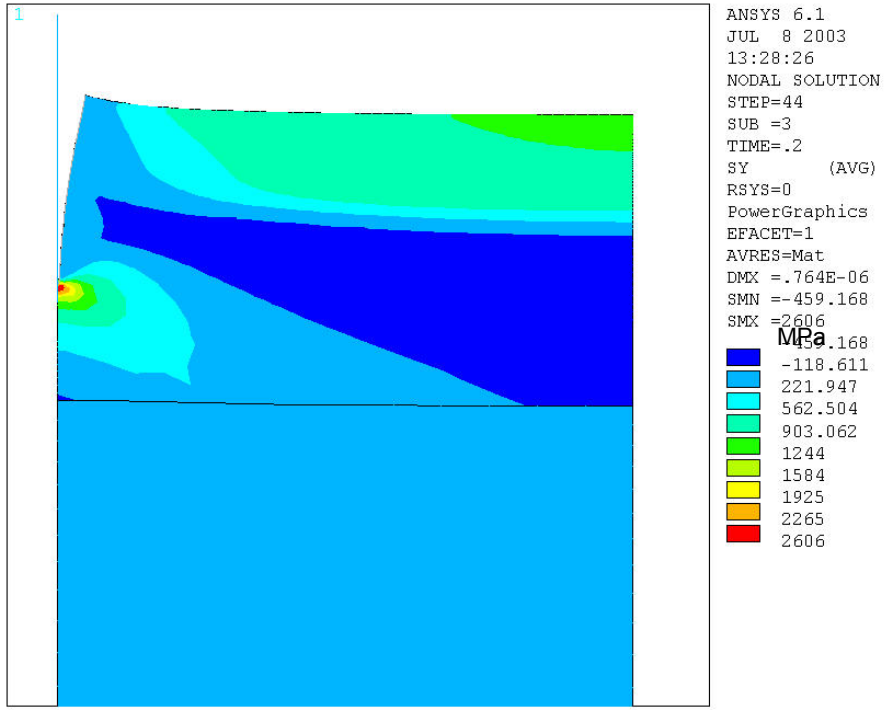
6.5 m chamber
154 MJ target
No gas
50 microns W

Stresses Resulting from Thermal Cycle

Stresses at Maximum Temperature



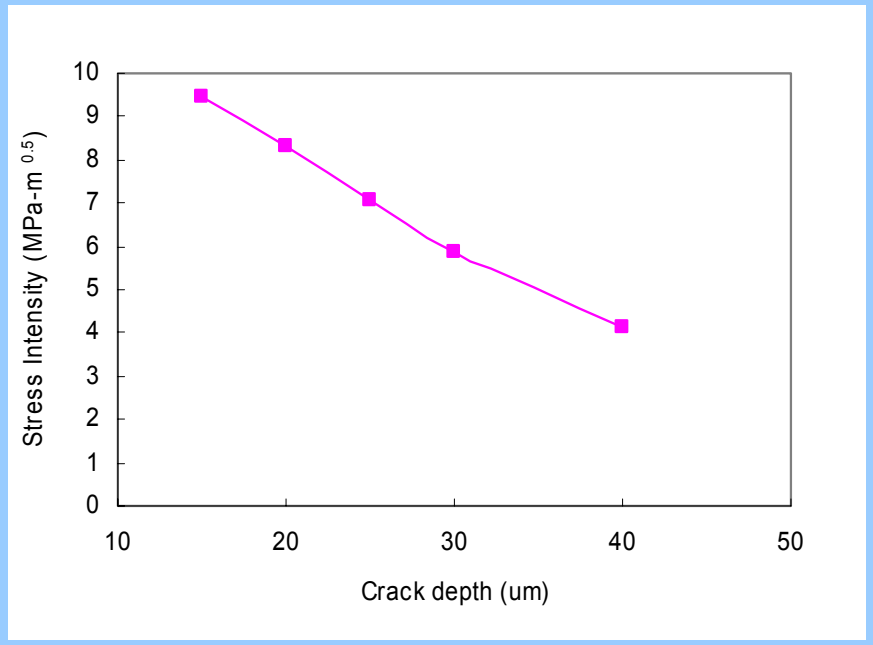
Stresses After Cool Down



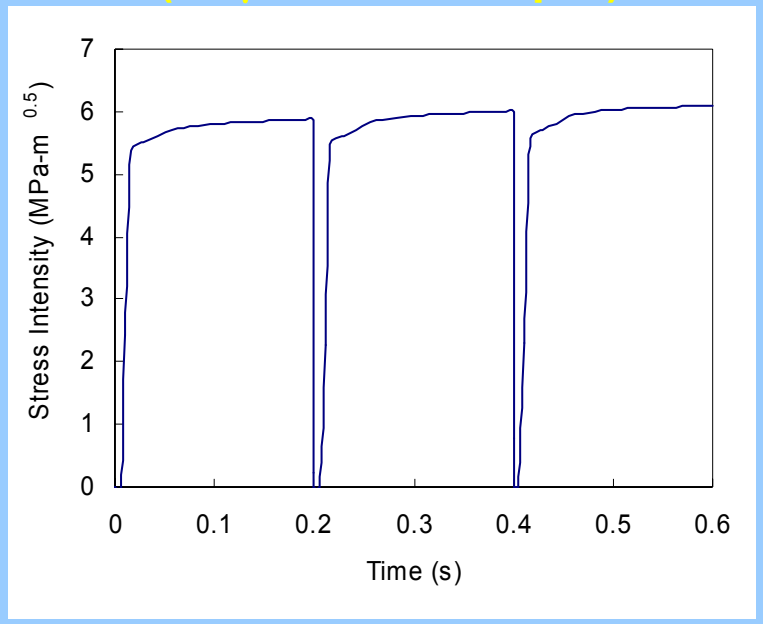
Fracture Mechanics Analysis Results

- Maximum stress intensities occur at end of cycle (when structure is cool).
- Stress intensity decreases with increasing crack depth

Stress Intensity vs. Crack Depth After One Thermal Cycle



Transient Stress Intensity (30 μm Crack Depth)



Conclusions

- Simple models can provide very accurate estimates of elastic stresses due to surface heating
- Significant plasticity is expected in reactor relevant chamber designs
- Tungsten armor is expected to crack and fracture analysis will be critical