Design and Analysis of an Innovative First Wall Concept

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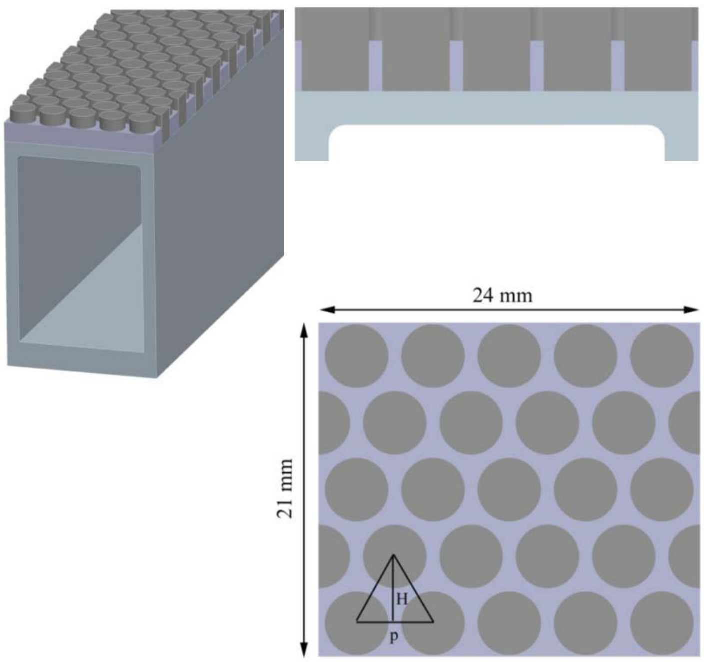
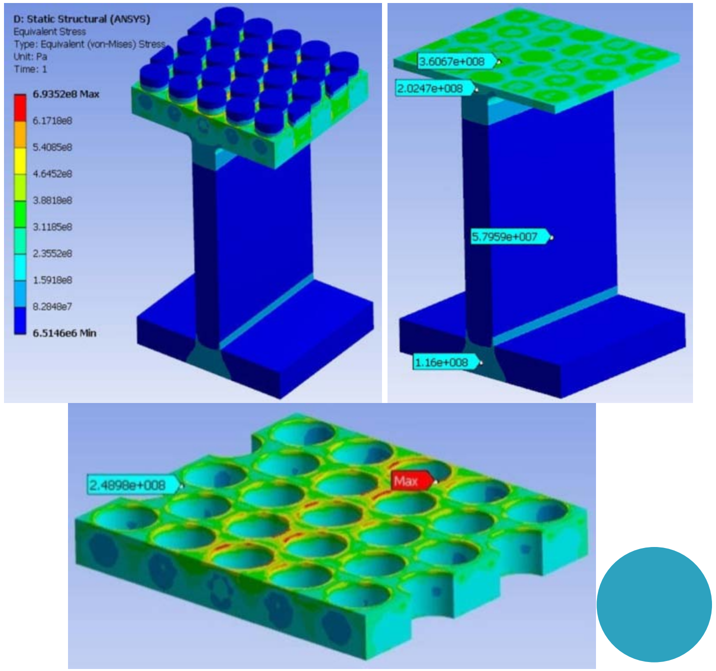
FW Armor Design and Analysis Results Presented at Last ARIES Meeting

- An innovative FW armor concept was proposed, similar to micro brush concept developed for ITER divertor target. It is a combination of W and ODS-steel for transient heat flux up to 2 MW/m^2.
- Thermo-mechanical calculations confirmed that the FW could only accommodate a steady-state heat flux up to 1.0 MW/m^2 if the structural behaviors were limited in the elastic region ($3S_m$ limits of ASME code).

ITER outboard target



ARIES FW armor concept

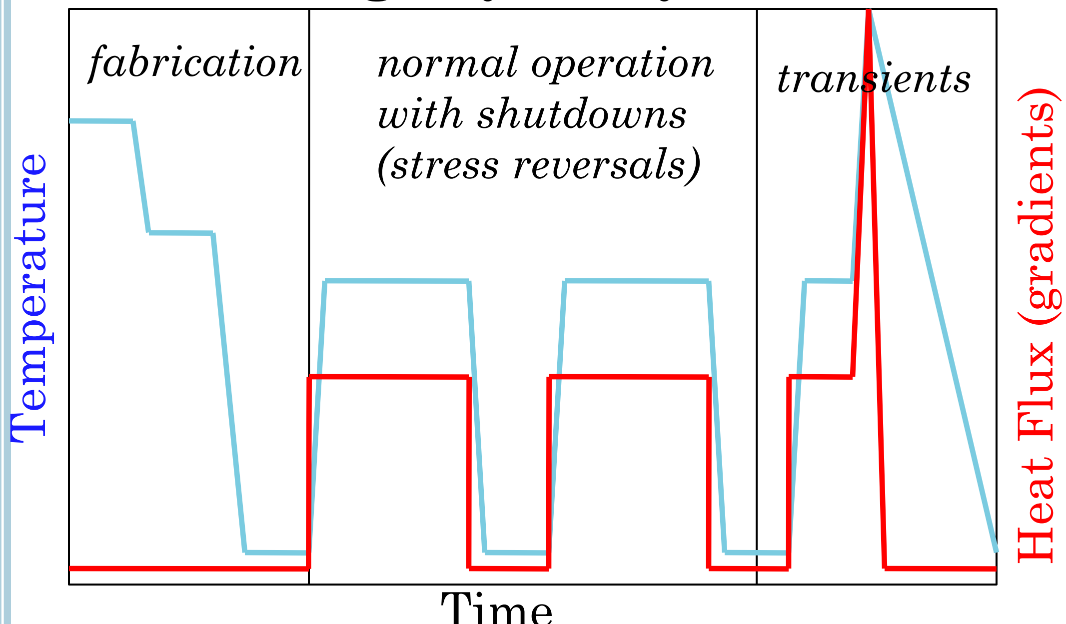


Results of the elastic structural analysis

DESIGN METHODS FOR HIGH TEMPERATURE COMPONENTS AS ALLOWED BY ASME CODE

(Mark's viewgraph presented at US/Japan Workshop on Feb. 20-21,2010)

- **Allow local yielding, and consider plasticity, ratcheting, shakedown, strain hardening, creep and additional phenomena**
- **Analyze a limited number of transient loading conditions**
- **Use "Design by Analysis" rather than "Design by Rule"**



- ASME is conservative; "Design by Analysis" limits may be higher due to plasticity, stress relaxation, strain hardening, *etc*.
- Extensive modeling and experimental verification are needed

Design Criteria Utilized by NET Team and FZK Divertor Team

- Maximum principal strains accumulated over the operating life should be less than 50% of the uniform elongation.

  $\varepsilon_{pl} < \varepsilon_{allow}$

  ε_{pl} : Maximum value of the principal strains

  ε_{allow} : 50% of the uniform elongation

  - Uniform elongation is defined as the plastic component of the engineering strain at the time when necking begins in a uniaxial tensile test
- Behavior of ratcheting
  - ✓ Definition of ratcheting:

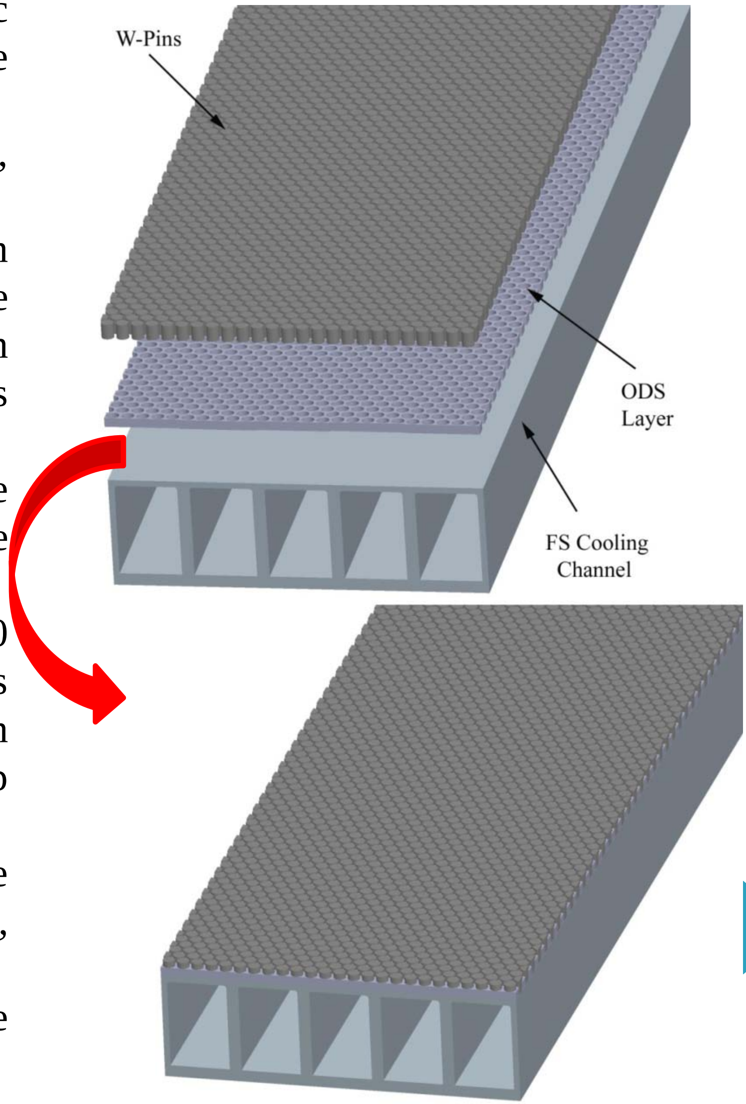
    a progressive deformation (accumulation of plastic strain) occurs when a structure is subjected to cyclic loading.
  - ✓ Behavior of Ratcheting:
    - Unlimited continuation -> failure of the component
    - Ceased ratcheting -> plastic shakedown

[1]. J. Reiser, "Assessment of a Brazed Transition Joint between WL10 Thimble and ODS Eurfer Structure," FZK, Germany, 2007.

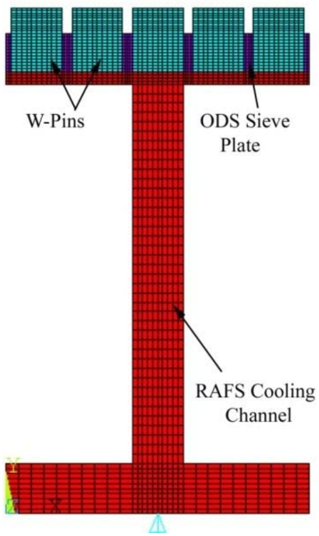
[2]. J. Reiser, P. Norajitra, R. Ruprecht,"Numerical investigation of a brazed joint between W-1%La_2O_3 and ODS EUROFER components," Fus.& Desg., ***83*** *(2008) 1126-1130.*

Suggested FW Fabrication Method

- Fabricate the FW cooling panel by HIP (Hot Isostatic Pressing) bonding together the rectangular cooling ducts made of RAFS.
- Lay the ODS sieve plate, the W-pins, and the brazing foils, rings or pastes on the top of the FW cooling panel.
- Put the entire assembly without any mechanical constrain into a furnace and heat it up slowly to the brazing temperature (1000~1100 °C) and braze them together. At this high temperature and long time, any fabrication residual stresses will be released.
- Cool the assembly down to the room temperature to seal the brazing joints. Some local plastic deformation by exceeding the yield strength will occur during this transient.
- Heat the assembly up to the tempering temperature (700~750 °C) and hold the temperature for ~ 1 hour. Most of the stresses in the RAFS will be released by exceeding the yield strength and by thermal creep, but the temperature is too low for creep relaxation for the W.
- Cool the assembly down to the room temperature, some plastic deformation by exceeding the yield strength may occur, especially in the RAFS cooling ducts.
- All the processes of fabrication and heat treatment will be completed in the furnace.



FE Model and Loading Cycles For the FW Fabrication Steps



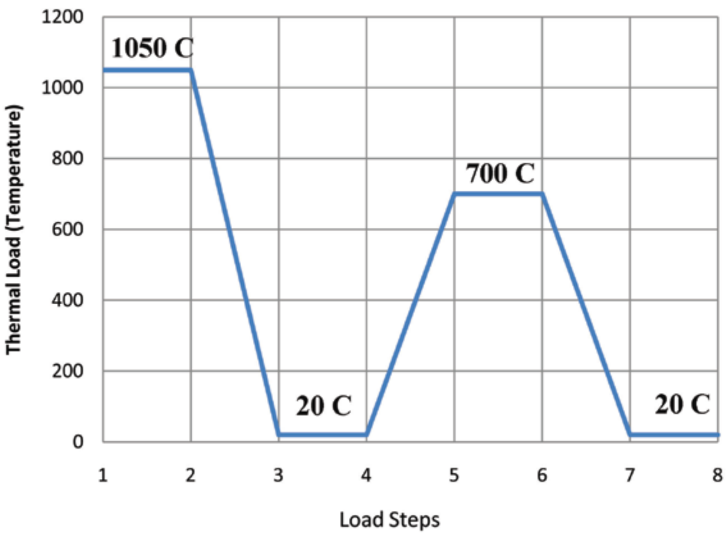
➢Key issue for the feasibility of concept is if the plastic deformation will be within allowable strain during the fabrication because large mismatch of thermal expansion coefficient between W and ODS/or RAFS causes high thermal stresses.(α_W=4.62*10^{-6} [1/K], α_{F82H}=10.6*10^{-6} [1/K] at 20 ºC)

➢ANSYS elastic-plastic model is used:

- ❑Bilinear Isotropic Hardening Material Model (BISO)
- ❑Linear elastic, perfect-plastic model without creep (no creep data)
- ❑Stress-free temperature assumed to be1050 °C (Brazing temperature)
- ❑No mechanical constrains during fabrication steps
- ❑No pressure load

1. Starting from brazing temperature, T=1050 °C
2. Holding at temperature of 1050 °C for 30 minutes
3. Cooling the FW uniformly down to RT to seal the joints for 30 minutes
4. Holding the RT for 30 minutes
5. Heating the FW uniformly up to tempering temperature (700~750 °C) for 30 minutes
6. Holding the tempering temperature for 30 minutes
7. Cooling the FW uniformly down to the RT for 30 minutes

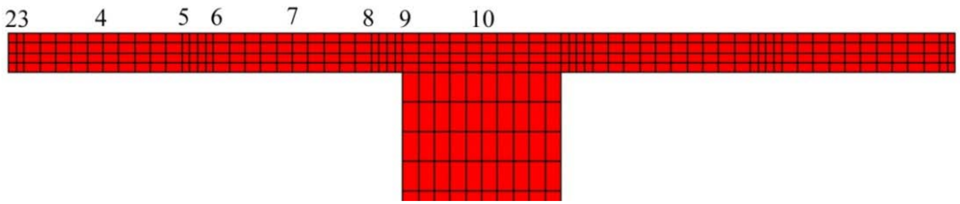
✓ Repeating 3-7 for additional thermal cycles (if it is necessary)



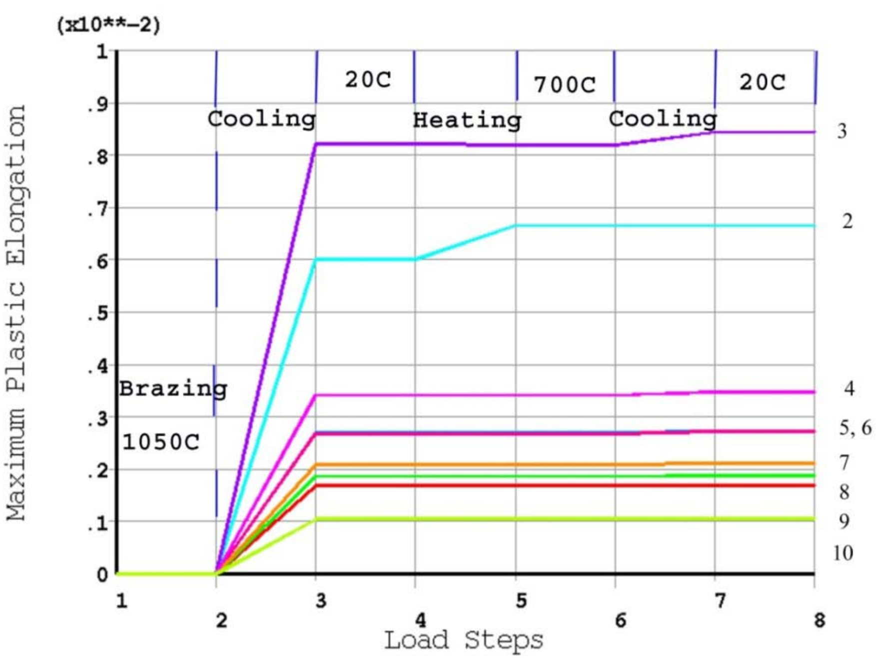
Plastic Strains at the Brazing Interface of the F82H Side

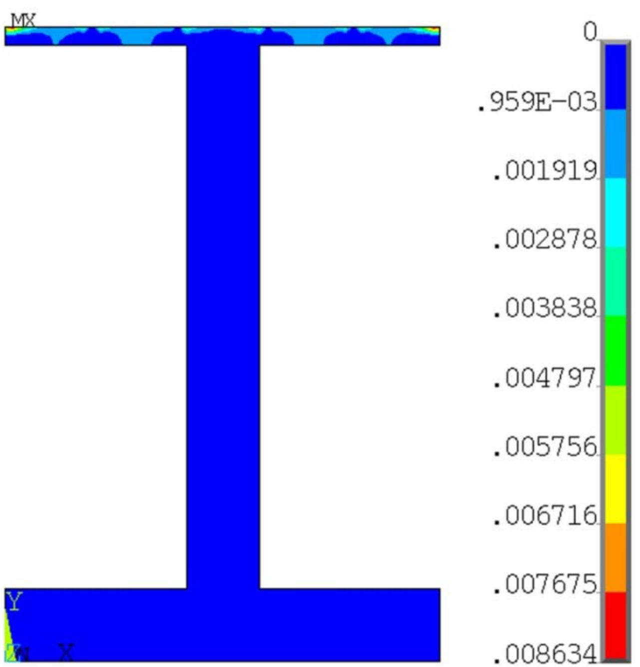
➢The plastic strain at the interface of the F82H stays in the allowable limit (ε_{allow} =1.1%) after the fabrication steps.

➢The maximum plastic strain is 0.85% after the fabrication and it would goes up to 0.86% after 5 cycles and reach saturation or steady-state.



Partial FE model and artificial node numbers

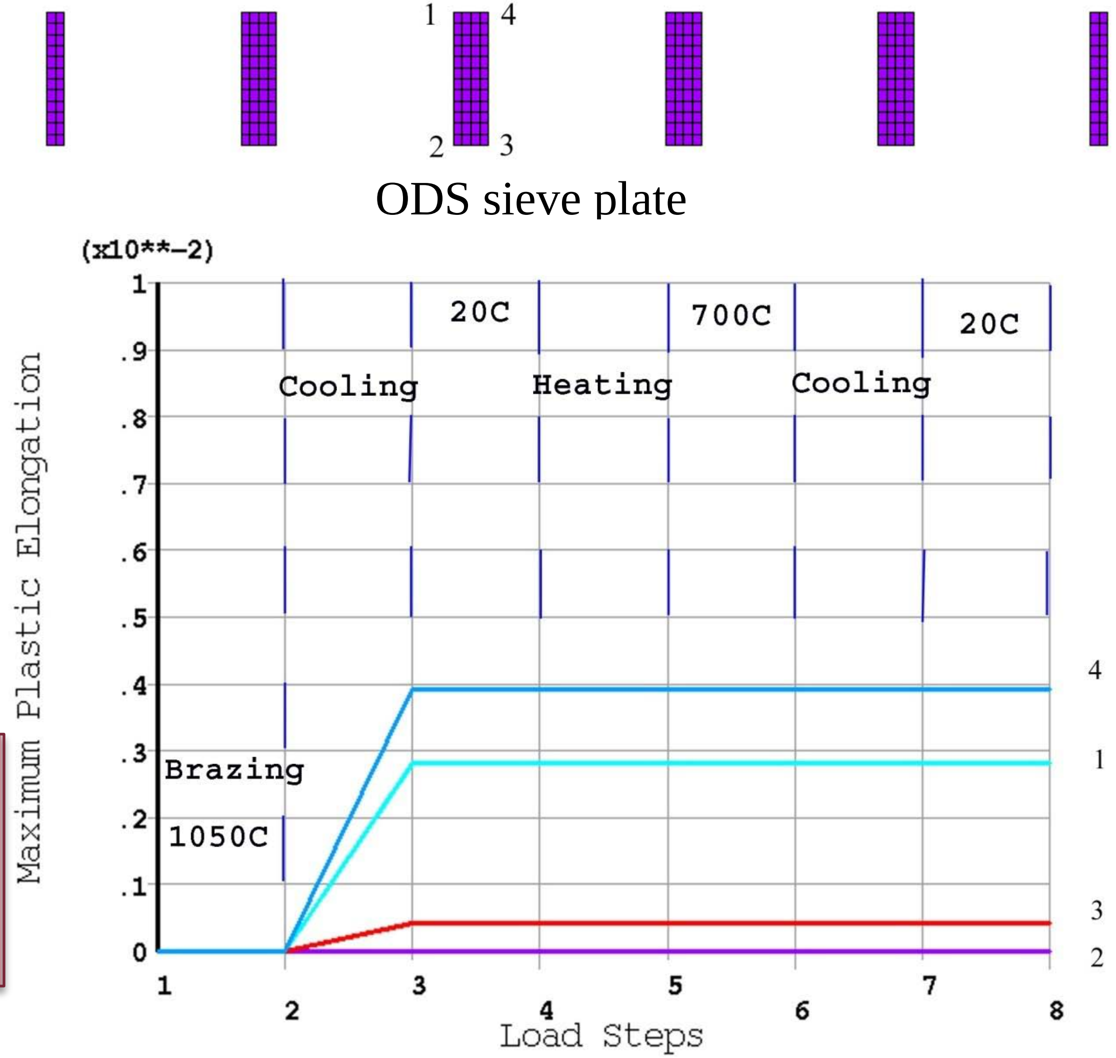




Plastic strain after 1000 cycles

Plastic Strains at the Brazing Interface of the ODS Sieve Plate

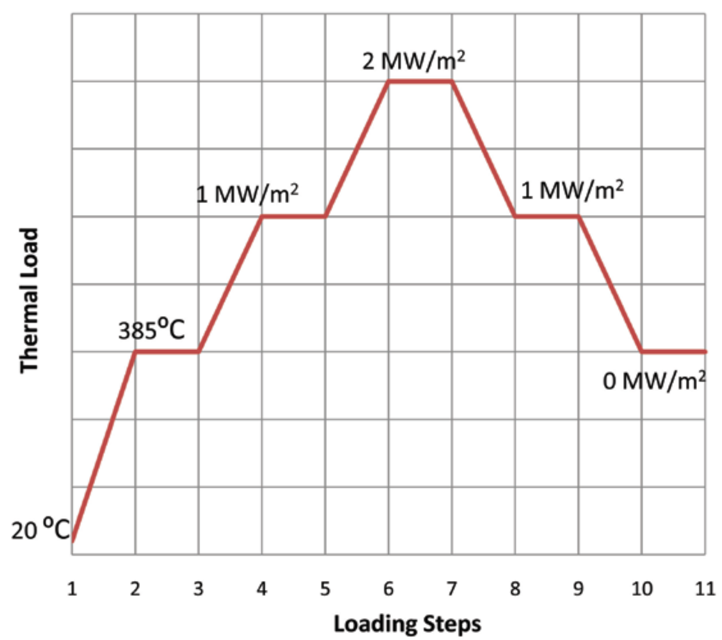
- The max. plastic strain at interface of ODS sieve plate is ~0.39%.
- The plastic strain reaches saturation when the assembly cooling down to RT from brazing temperature at the load step 3.
- The max. elastic strain at interface of W-pins is about 0.27%.



Conclusion: The FW survives during the fabrication and heat treatment.

Cyclic Loads for Transient Operation with Warm Shut-down

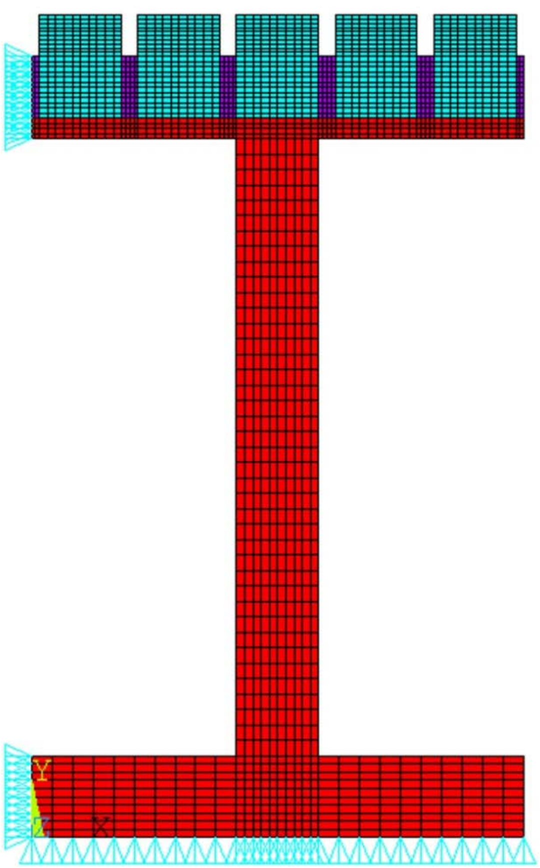
1. Room temperature is applied at t=0
2. The FW/Blanket is heated up slowly to the coolant temperature of ~385 °C (Δt= 1 hour)
3. The temperature is held at 385 °C for 1 hour
4. Plasma power is on, and the power is raised to operational value (q"=~1 MW/m^2) in the order of seconds (Δt=50 s)
5. Surface heat flux is held at 1 MW/m^2 for 1 hour
6. A fast transient occurs and the surface heat flux rises to ~2 MW/m^2 in the order of seconds (Δt=1 s)
7. The transient is held at 2 MW/m^2 for 5 s
8. The plasma power goes back to normal operation (q"=~1 MW/m^2) in the order of seconds (Δt=1 s)
9. Surface heat flux is held at 1 MM/m^2 for 1 hour
10. Plasma power is off in 50 second (q"=0)
11. The FW assembly is operated at the coolant temperature ~ 385 °C (Δt= 1 hour)



Loading profile for a operation with warm shut-down
(1 cycle=10 loading steps)

✓Pressure load P=8 MPa is applied at the time step 2. Additional thermal cycles are applied by repeating 3-11 steps.

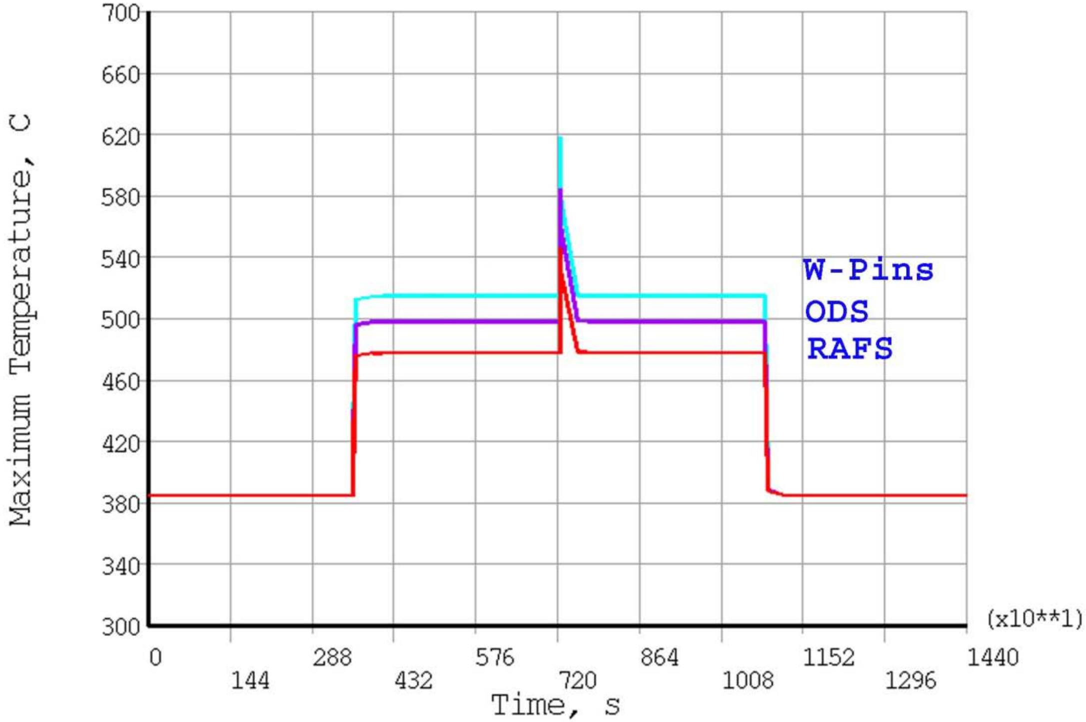
ANSYS Thermo-Mechanical Model and BCs

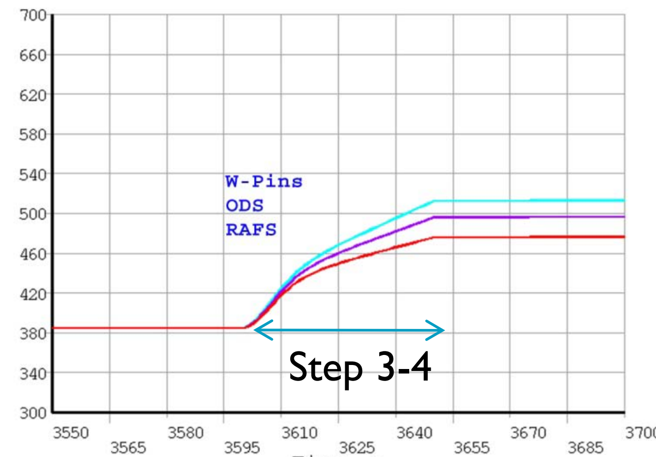


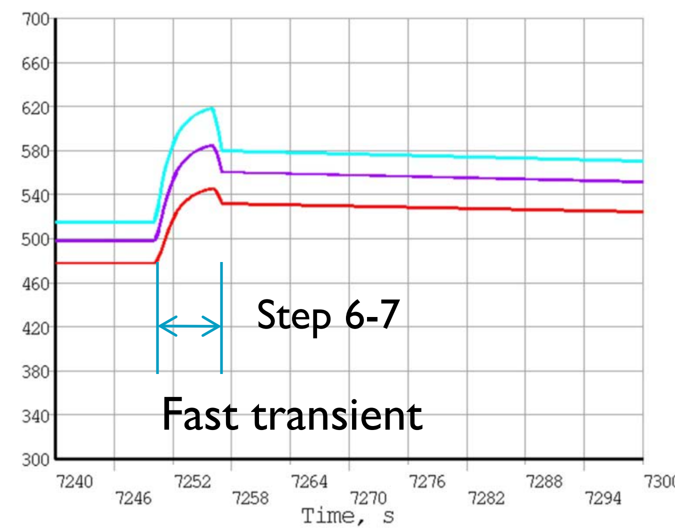
ANSYS FEA Model

- ANSYS Bilinear Isotropic Hardening Material Model (BISO, preferring for large strain analysis)
- Linear elastic, perfect-plastic stress-strain relations
- A 2D ANSYS plane strain model and element PLANE182
- Time-dependent temperature loads directly coupled to the structural model
- *Stress-free temperature assumed to be the brazing temperature of 1050 ℃(It is a conservative assumption because it maximizes the temperature differences between SFT and RT as well as the differences between SFT and operation temperature)*
- All nodes at the bottom, Uy=0
- All nodes at one side, Ux=0, another side free to expand
- Pressure loads, P=8 MPa
- No thermal creep included because of lacking data

Thermal Results Showing FW Meets Temperature Limits During Operation with Warm Shut-down



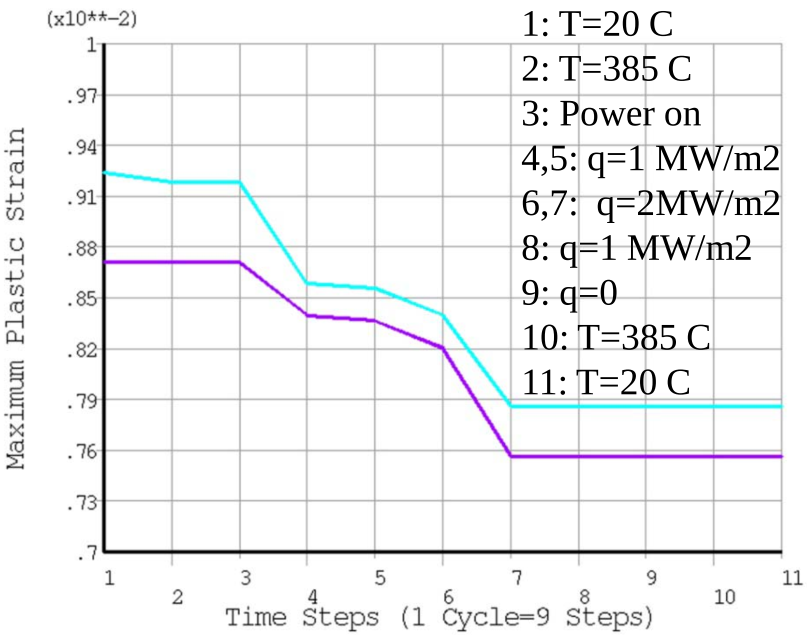




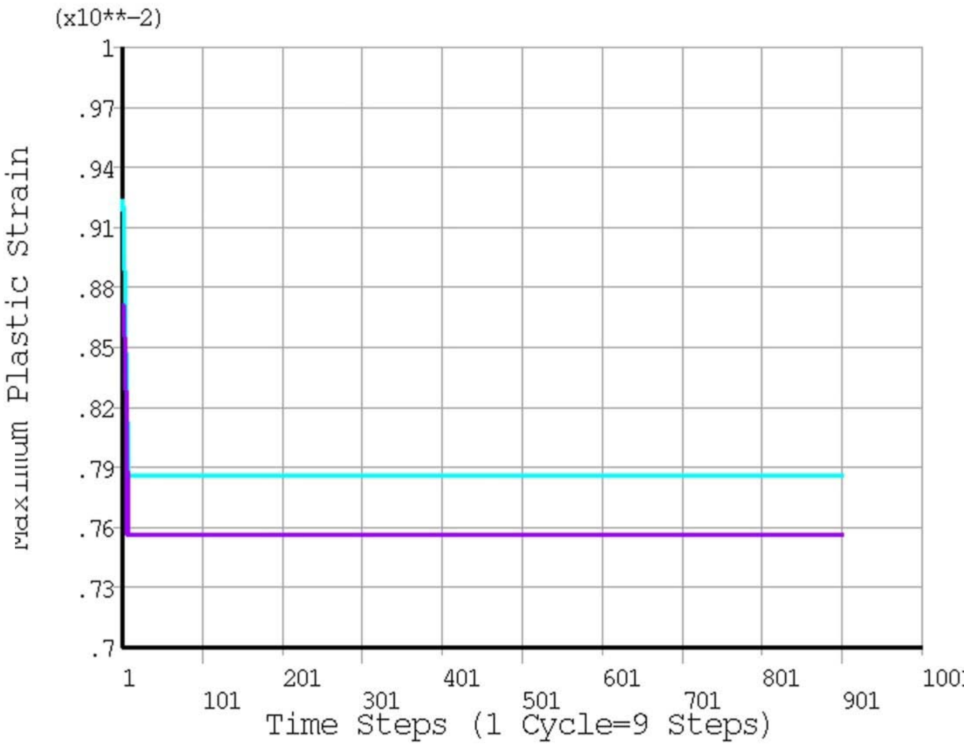
- ➢Heat transfer coefficient was scaled from ARIES-CS FW design (q''=0.76 MW/m^2), and htc~2.3x10^4 W/m^2-K
- ➢Results show that the temperature of the FW meets temperature limits.
  - ✓T_{max} (W)=618 ^{o}C, T_{max} (ODS)=582 ^{o}C (<700 ^{o}C),
  - ✓T_{max} (RAFS)=542 ^{o}C (<550 ^{o}C)

Plastic Strain at the Brazing Interface of the F82H Side

- The max. plastic strain at the interface of the F82H side, ε_{pl}= 0.92% (< ε_{allow} =1.1%) at the RT.
- There is no ratcheting observed after 100 load cycles.
- The plastic strain reaches saturation in the first load cycle, and the max. saturated plastic strain ε_{pl}= 0.79%



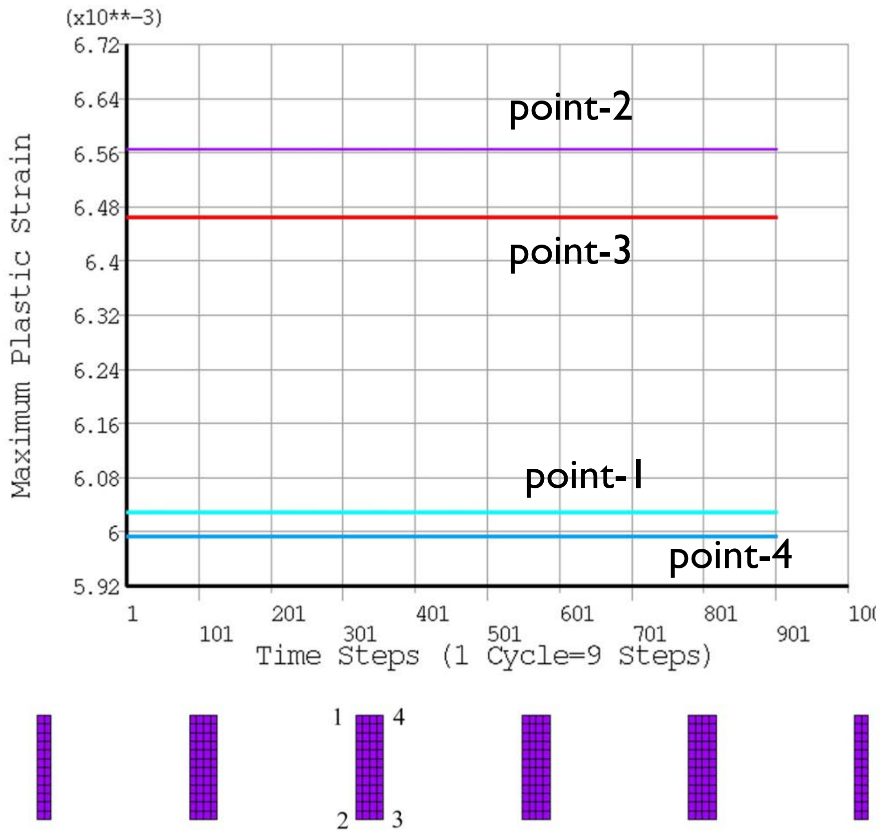
First Load Cycle



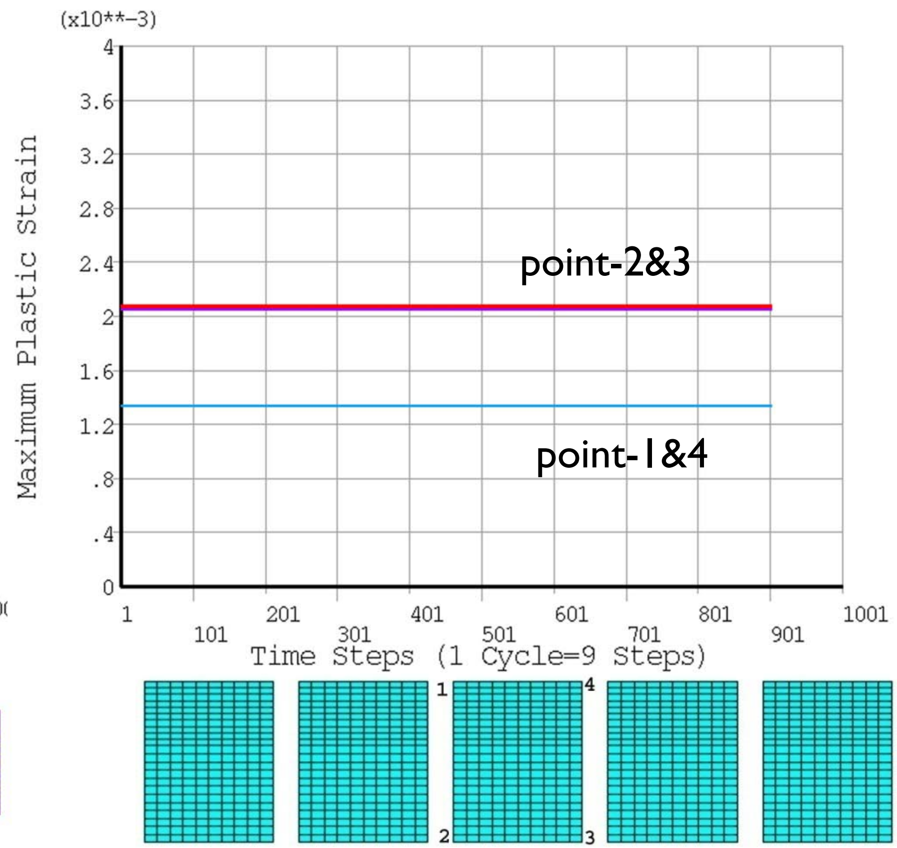
100 Load Cycles

Plastic Strain at the Brazing Interfaces of the ODS and W Sides

- The max. plastic strain at the interface of the ODS side, ε_{pl}= 0.66% (< ε_{allow} =1.1%)
- The max. plastic strain at the interface of the W-pin side, ε_{pl}= 0.21%
- There are no ratcheting for both of ODS and W-pins after 100 load cycles.



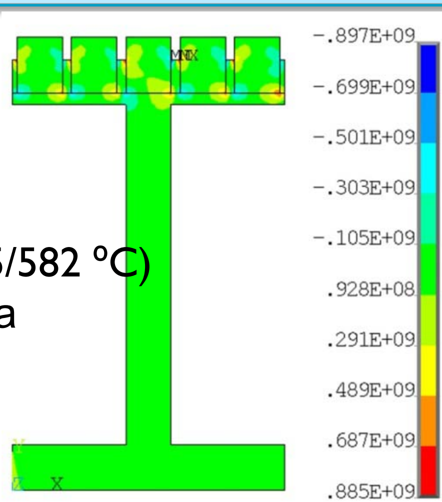
ODS sieve plate

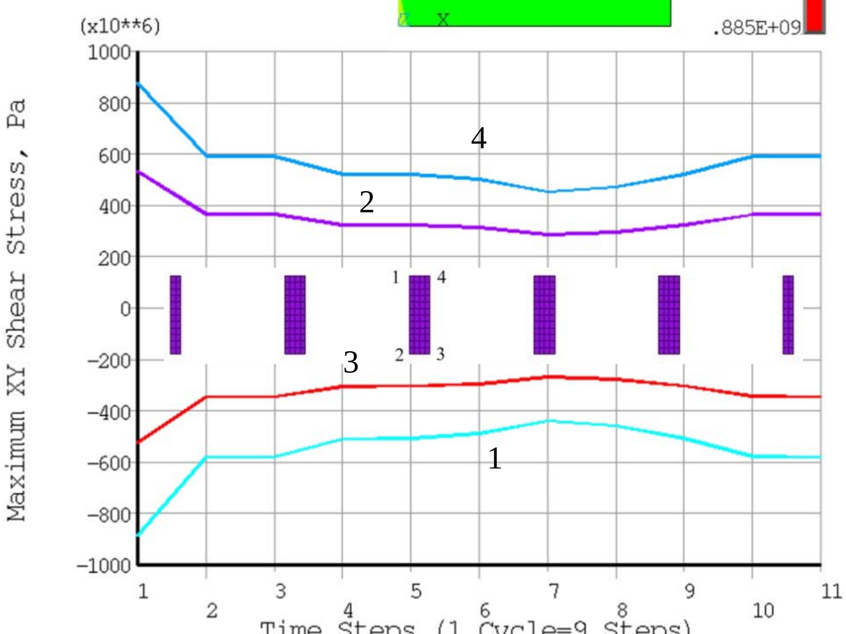


W-pins

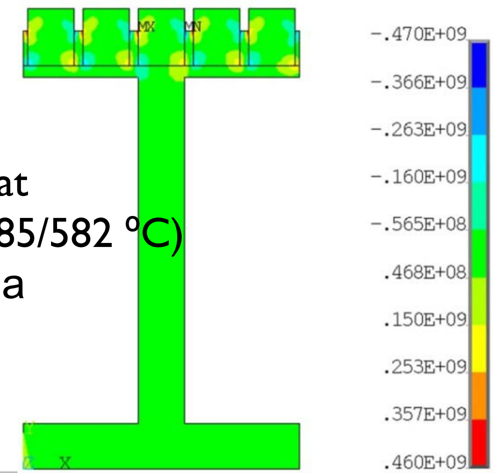
Example Comparison of Elastic/Plastic Structural Analysis

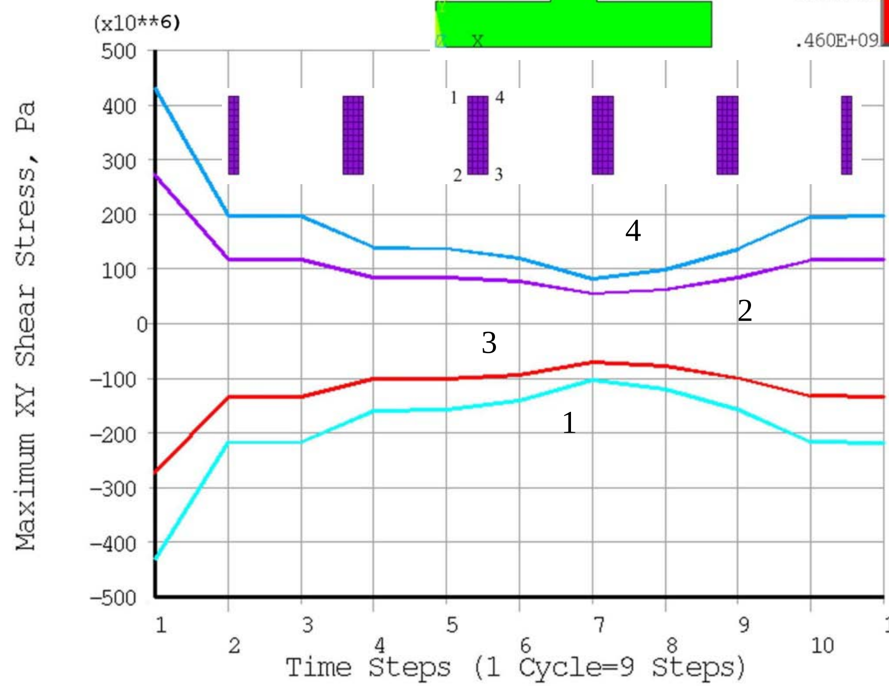
Elastic analysis:
Max. XY shear stress at
RT/CT/ODS OT(20/385/582 °C)
σ_{xy}=885/600/450 MPa





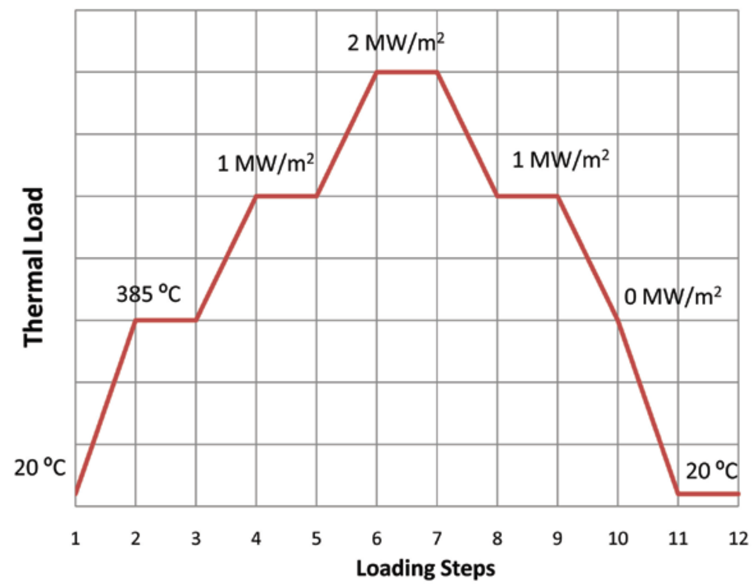
Elastic-Plastic analysis:
Max. XY shear stress at
RT/CT/ODS OT(20/385/582 °C)
σ_{xy}=460/200/90 MPa





Cyclic Loads for Transient Operation with Cold Shut-down

1. Room temperature is applied at t=0
2. The FW/Blanket is heated up slowly to the coolant temperature of ~385 ºC (Δt= 1 hour)
3. The temperature is held at 385 ºC for 1 hour
4. Plasma power is on, and the power is raised to operational value (q”=~1 MW/m^2) in the order of seconds (Δt=50 s)
5. Surface heat flux is held at 1 MW/m^2 for 1 hour
6. A fast transient occurs and the surface heat flux rises to ~2 MW/m^2 in the order of seconds (Δt=1 s)
7. The transient is held at 2 MW/m^2 for 5 s
8. The plasma power goes back to normal operation (q”=~1 MW/m^2) in the order of seconds (Δt=1 s)
9. Surface heat flux is held at 1 MM/m^2 for 1 hour
10. Plasma power is off in 50 second (q”=0)
11. The FW assembly is cooled uniformly to the room temperature (Δt= 1 hour)
12. The temperature is held at the room temperature for 1 hour

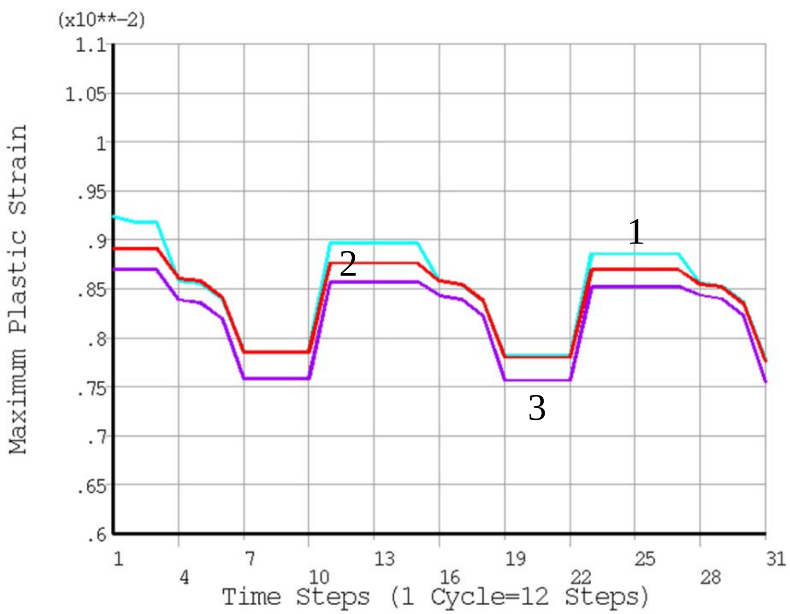


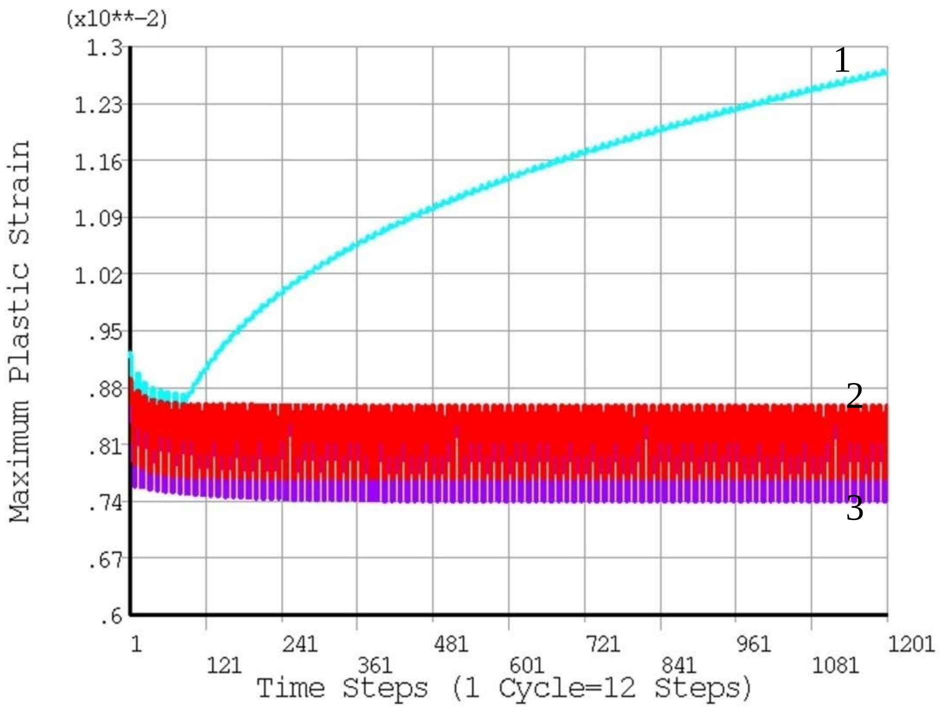
Loading profile for a operation with cold shut-down
(1 cycle=11 loading steps)

✓Pressure load (P=8 MPa) is applied at the step 2 and removed at the step 11. Additional loading cycles are applied by repeating 1-12 steps.

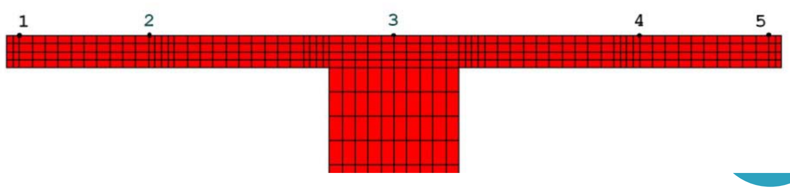
Plastic Strain at the Brazing Interface of the F82H Side

- The plastic strain reaches the allowable limit (< ε_{allow} =1.1%) after ~40 loading cycles
- It would go up to ε_{pl}= 1.27% after 100 cycles.
- However, the potential for ~40 cycles during the lifetime of the blanket down to RT(~20^{o}C) requiring draining of liquid metal from the blanket is probably sufficient.





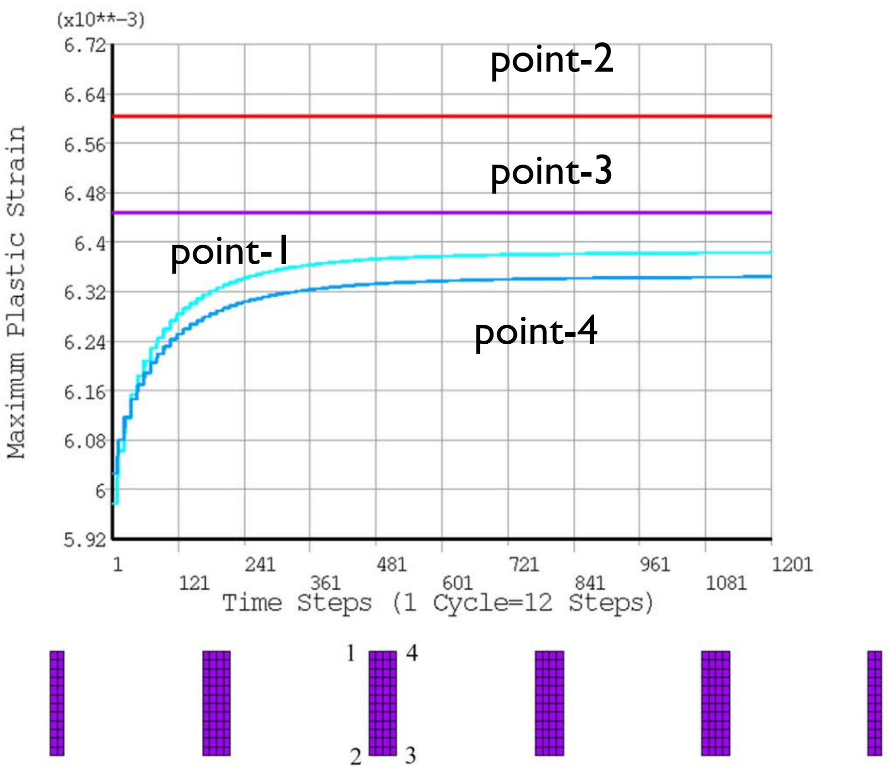
100 Load Cycles



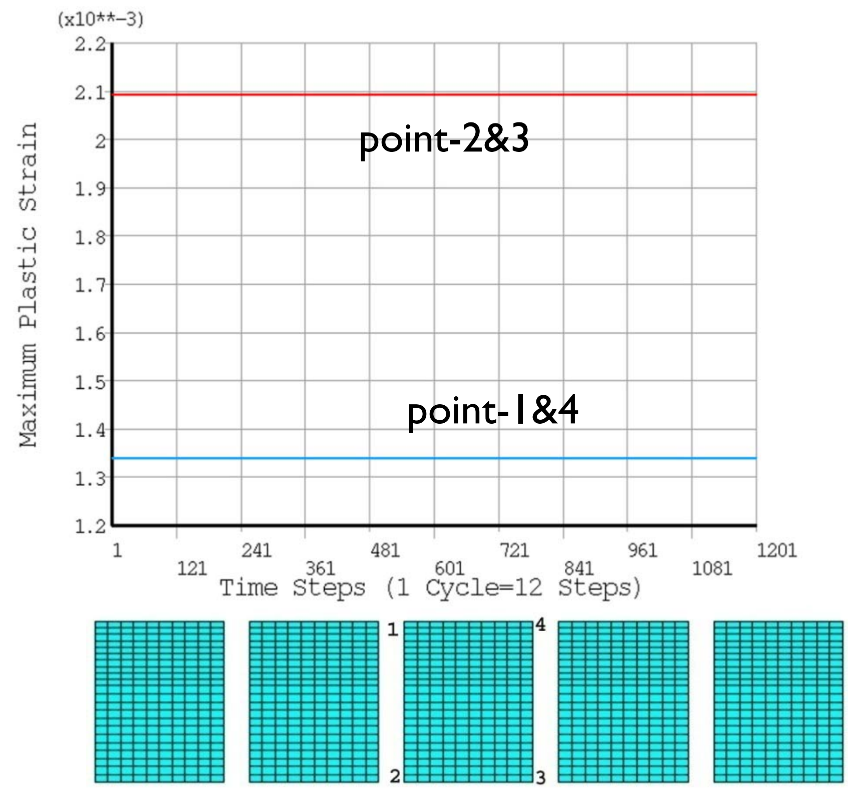
Partial FE model showing artificial node numbers

Plastic Strain at the Brazing Interfaces of the ODS and W Sides

- The max. plastic strain at the interface of the ODS side, ε_{pl}= 0.66% (< ε_{allow} =1.1%), and ratcheting is shakedown after ~50 load cycles.
- The max. plastic strain at the interface of the W-pin side, ε_{pl}= 0.21% (< ε_{allow} =1.1%)
- The plastic strain of the W-pins reaches saturation at the first step.



ODS sieve plate



W-pins

Summary and Future Work

- Progress on the elastic-plastic analysis has been made.
- The results of plastic analysis indicate that the FW assembly meets the plastic criteria (< ε_{allow} =1.1%) during fabrication and transient operation with warm-shutdown scenario.
- The FW concept can only survive ~40 loading cycles for the transient operation with cold shut-down. However, 40 cycles down to room temperature may probably be sufficient for the life time of the FW/Blanket(3-5 years).
- Modification of the FW armor design may be helpful to lower the plastic strain, for example, increasing the 1.0 mm thick RAFS front-plate to 2.0 mm may help reduce the plastic strain of the RAFS structure or the plastic shakedown may occur.
- 3D elastic-plastic analyses may be needed to confirm the non-linear structural behaviors of the FW armor.
- Creep of the FW assembly is not included in the present analysis. The temperature of the ODS steel as well as for the W-pins are not sufficiently high for significant creep. In future analyses, thermal creep and irradiation induced creep of the RAFS structure will be included when data becomes available.