

Analysis Results for New First Wall Protection Schemes

Presented By: X.R. Wang
Contributors: S. Malang and M. Tillack

ARIES-Pathways Meeting
GA, San Diego
December 15-16, 2009

ARIES-CS DCLL BLANKET DESIGN AND FINAL RESULTS

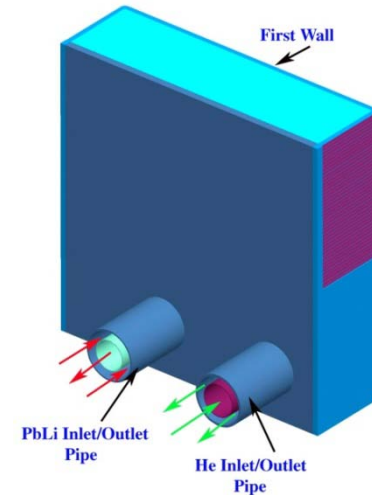
Features and parameters

- 2 m x 2 m modular blanket, He-cooled FW
- 3 mm ODS FS plate brazing over 1 mm FS layer.
- He operation pressure $P=10$ MPa
- Surface heat flux, $q_s=0.76$ MW/m²
- Volumetric heat generation $q_v=44$ MW/m³
- He inlet/outlet FW and outlet module $T=385/430/460$ °C
- Heat transfer coefficient in FW channel $htc=8825$ W/m²-K

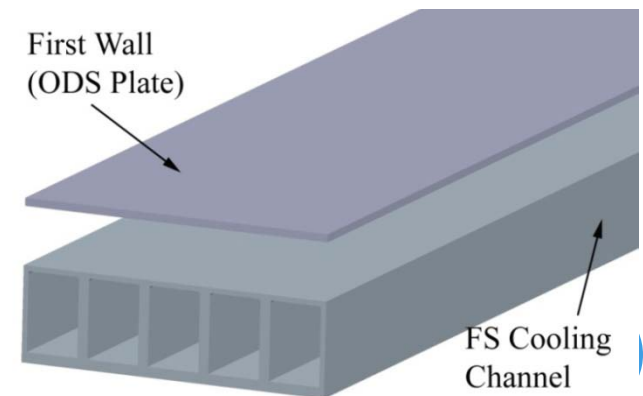
FW/blanket results and performance:

- Gross power cycle efficiency=43%, net efficiency=39.0%
- Max. ODS FS temperature=642 °C (<700 °C)
- Max. RAFS temperature=546 °C (<550 °C)
- Max. combined primary and secondary stresses for ODS FS $\sigma=654$ MPa (3Sm=660 MPa for ODS 12YWT at $T=650$ °C)
- Max. combined primary and secondary stresses for FS $\sigma=390$ MPa (3Sm=354 MPa for FS at $T=550$ °C)

Both material temperature and stresses reached the design limits without design margin based on 3 Sm.



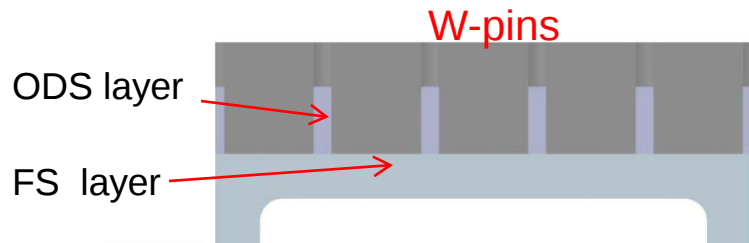
ARIES-CS DCLL modular blanket



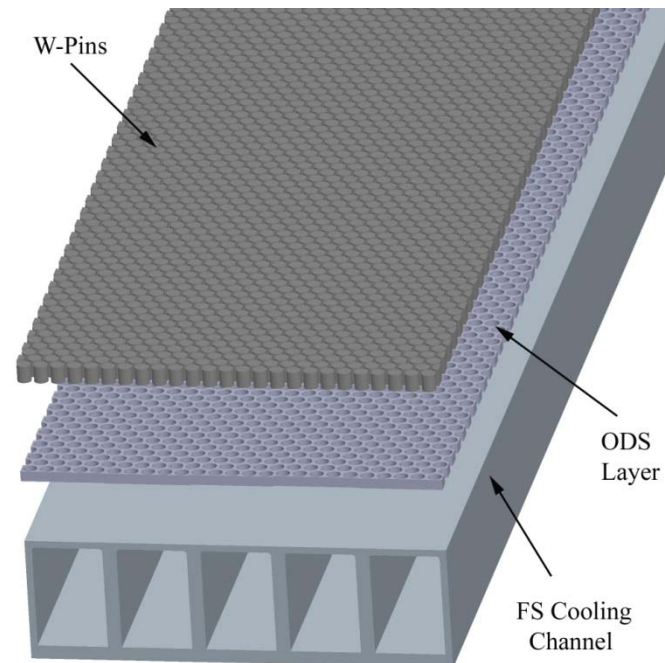
3-mm ODS plate brazed on the FS cooling channel

NEW FIRST WALL ARMOR DESIGN (PROPOSED BY SIEGFRIED MALANG)

- Design goals are to accommodate a heat flux of 1 MW/m^2 in a steady state operation and up to 2 MW/m^2 at transient events.
- Design concept is to embed a micro-brush like W-pins into a ODS plate; $\sim 65\%$ of total first wall surface area is covered by W, and $\sim 35\%$ by ODS steel. The effective conductivity of the first wall layer is $\sim 75 \text{ W/m-K}$ ($\sim 33 \text{ W/m-K}$ for ODS), reducing temperature gradient and thermal stresses.
- There are $\sim 80\%$ with normal FW and normal cooling and other regions ($\sim 20\%$) with added FW armor and much larger heat transfer coefficient.
- Suggested fabrication method for such a composite is to braze the FS layer, ODS steel layer, W-pins together in a furnace.

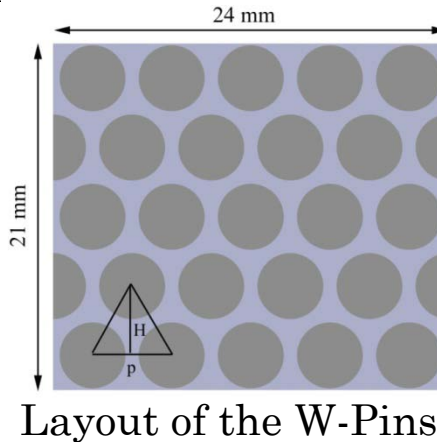
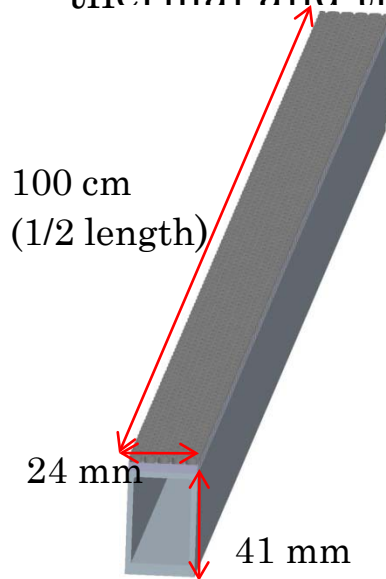


Brazing material: CuPd18 (Melting Point: $1080-1090^\circ\text{C}$), or Cu86MnNi (Cu86, Mn12, Ni2; MP: $970-990^\circ\text{C}$)

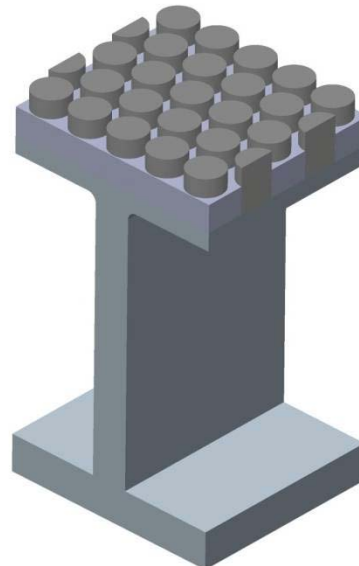


ANSYS THERMO-MECHANICAL MODEL OF THE FIRST WALL ARMOR

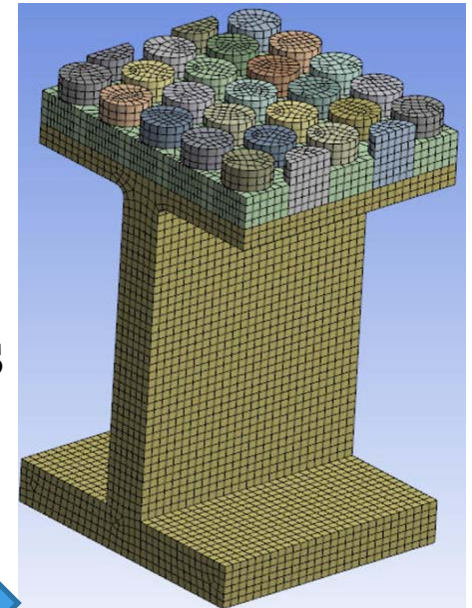
- To optimize geometry, dimensions and the layout of the W-pins based on thermal and thermo-mechanical results.



First wall channel: 20 x 30 mm
Thickness of ODS plate: 3 mm
Diameter of W-Pins: 4 mm
Depth of W-Pins: 5 mm
Pitch of the W-Pins: 4.8 mm
Thickness of RAFS: 2 mm
Thickness of back plate: 4 mm
Thickness of side wall: 4 mm



ANSYS
model

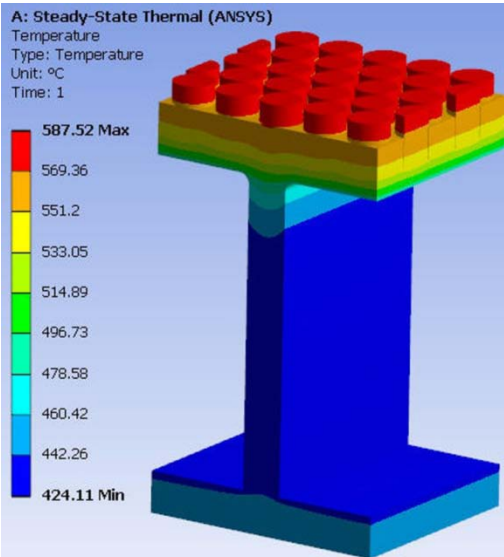


STEADY-STATE THERMAL LOADS AND COOLING CONDITIONS FOR THE FW ARMOR

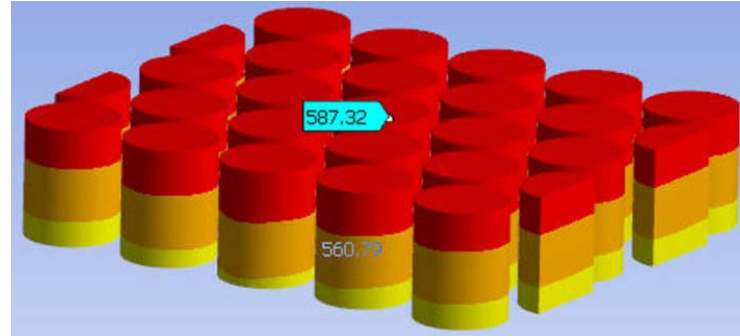
- Parameters, loads and cooling conditions for the FW armor
 - ✓ $q_s=1.0 \text{ MW/m}^2$ ($q_s=0.76 \text{ MW/m}^2$ for ARIES-CS), $q_v=44 \text{ MW/m}^3$ (neutron wall load= 5.25 MW/m^2)
 - ✓ Helium inlet/outlet temperature for the FW, $T_{in}/T_{out}=385/430 \text{ }^\circ\text{C}$, and helium blanket outlet temperature, $T_{blkt, out}=460 \text{ }^\circ\text{C}$ (same as ARIES-CS)
 - ✓ Coolant operation pressure, $P=10 \text{ MPa}$ (same as ARIES-CS)
 - ✓ Heat transfer coefficient in first-wall channel (front face with artificial roughness), $htc=1.16 \times 10^4 \text{ MW/m}^2\text{-K}$ (increased by ~24%)
 - ✓ Heat transfer coefficient in side walls and back plate, $htc=0.58 \times 10^4 \text{ MW/m}^2\text{-K}$ (increased by ~24%)
- Temperature-dependent properties are included in the ANSYS model.
- Elastic steady-state structural analysis is assumed in structural model.



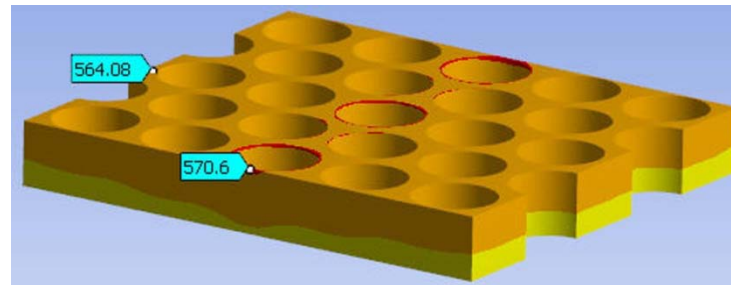
THERMAL RESULTS FOR THE FW ARMOR WITH A HEAT FLUX OF 1.0 MW/M²



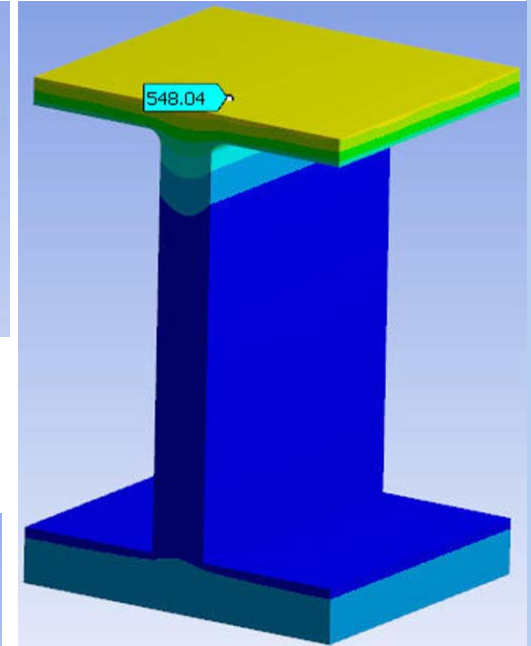
Temperature
distribution



$$T_{\max} (W) = 587 \text{ }^{\circ}\text{C} (<1300 \text{ }^{\circ}\text{C})$$



$$T_{\max} (ODS) = 570 \text{ }^{\circ}\text{C} (<700 \text{ }^{\circ}\text{C})$$

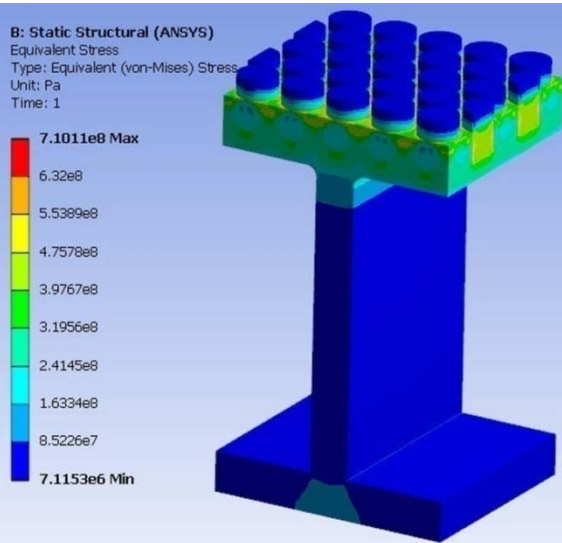


$$T_{\max} (FS) = 548 \text{ }^{\circ}\text{C} (<550 \text{ }^{\circ}\text{C})$$

➤ Thermal results indicate that the temperature of the first wall armor is below material temperature limits.



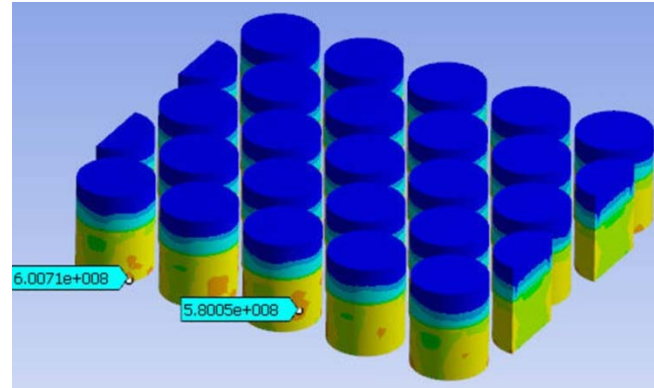
EXAMPLE ELASTIC STRUCTURAL ANALYSIS OF THE FW ARMOR



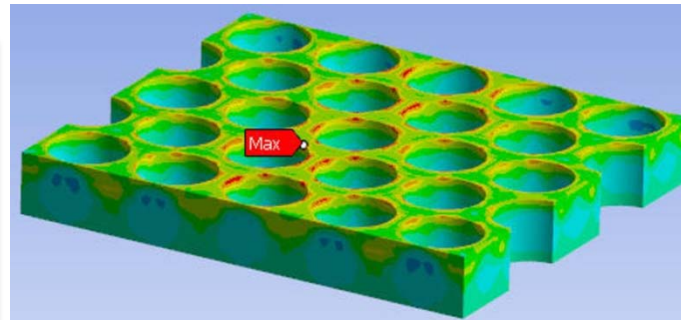
Stress distribution

➤ Stress calculations show that both the stresses of W-pins and ODS layer meet 3 Sm design criteria.

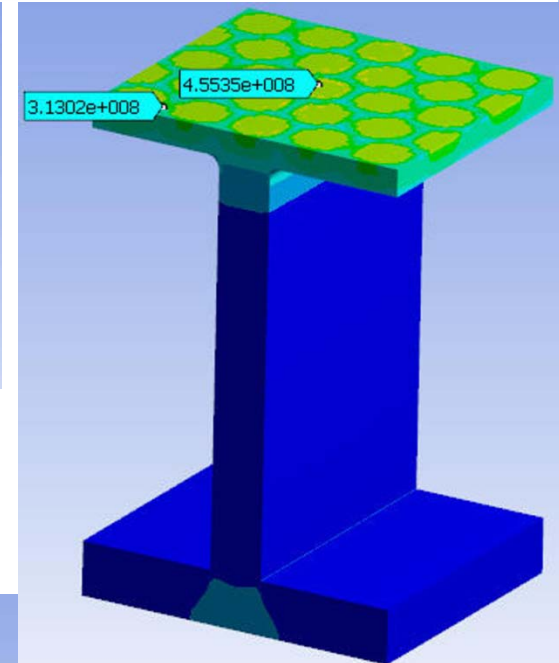
➤ Stresses of the FS layer are too high and exceed the yield strength.



$\sigma_{p+s} (W) = 600 \text{ MPa}$
(3 Sm = ~878 MPa for W at T=600 °C)



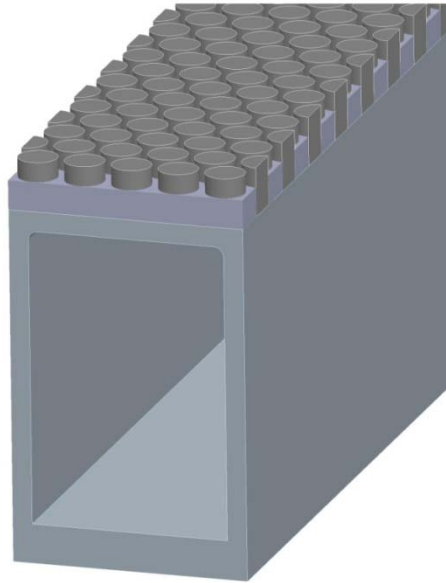
$\sigma_{p+s} (ODS) = 710 \text{ MPa}$
(3 Sm = ~1260 MPa for ODS 12YWT, and 399 MPa for F82H at T=600 °C)



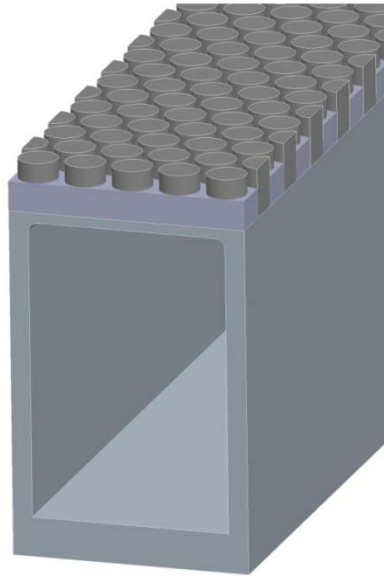
$\sigma_{p+s} (FS) = 455 \text{ MPa}$
(3 Sm = ~354 MPa for FS at T= 550 °C)



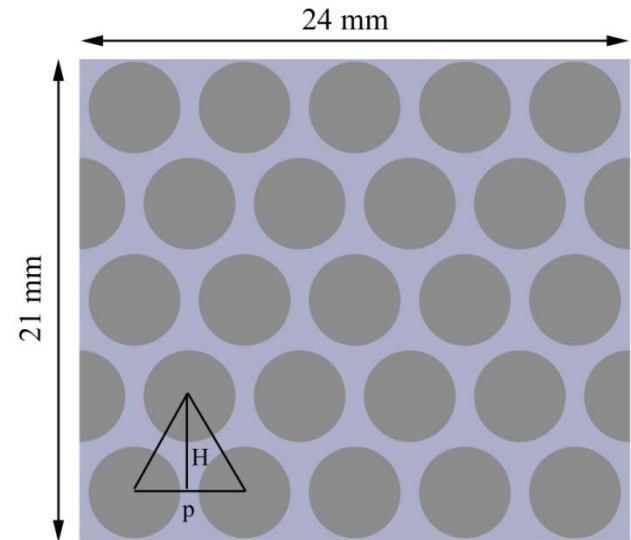
EXAMPLE TO REDUCE THICKNESS OF FS LAYER FROM 2 MM TO 1 MM



2 mm FS layer



1 mm FS layer



Layout of the W-pins

- The max. stresses at the FS layer exceed allowable design limitations based on the 3 Sm limits, therefore, one possibility of reducing the stresses is to reduce the thickness of FS layer from 2 mm to 1 mm.
- The thickness of the ODS plate and the layout of the W-pins are maintained the same.
- The thermal loads and cooling conditions are the same.

EXAMPLE THERMAL RESULTS FOR THE FW ARMOR (1 MM FS LAYER)

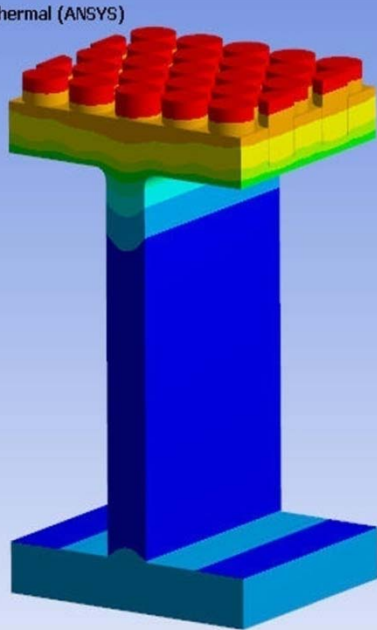
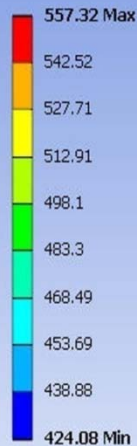
C: Steady-State Thermal (ANSYS)

Temperature

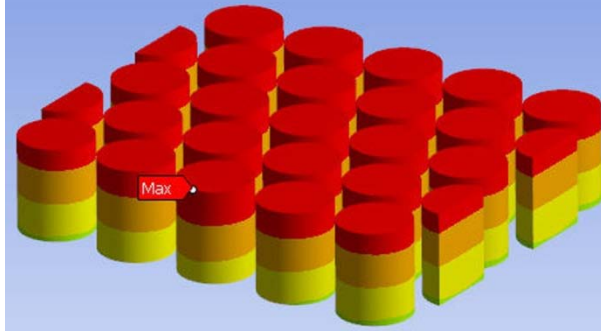
Type: Temperature

Unit: °C

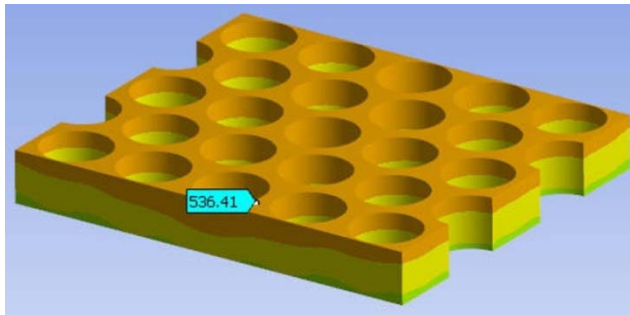
Time: 1



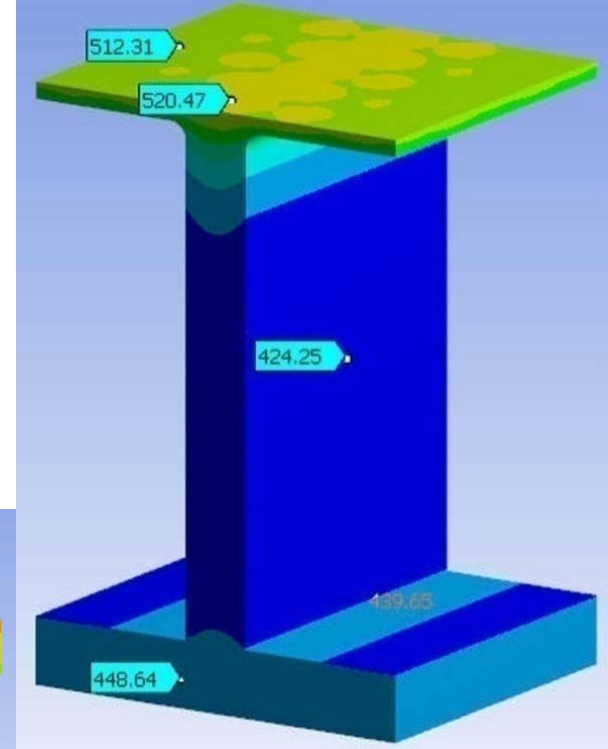
Temperature
distribution



$T_{\max} (W) = 557^{\circ}\text{C}$
($< 1300^{\circ}\text{C}$)



$T_{\max} (\text{ODS}) = 536^{\circ}\text{C}$ ($< 700^{\circ}\text{C}$)



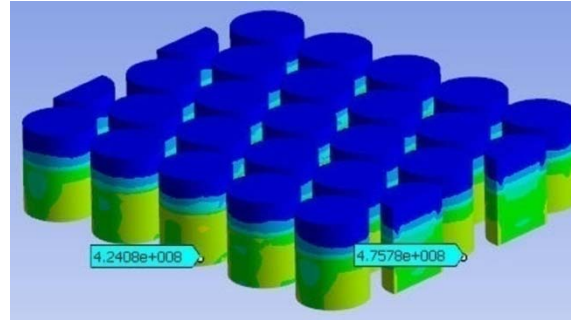
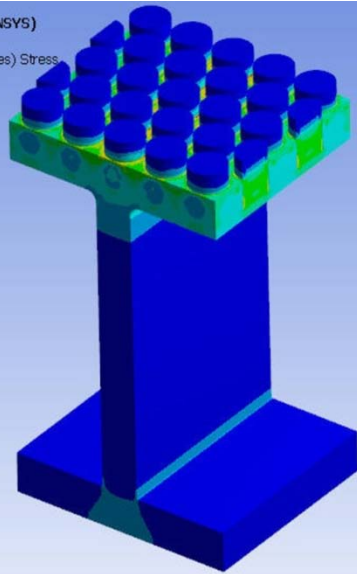
$T_{\max} (\text{FS}) = 512^{\circ}\text{C}$
($< 550^{\circ}\text{C}$)

➤ Temperature results show a comfortable design margin for the FW armor with a 1 mm thickness of FS layer.

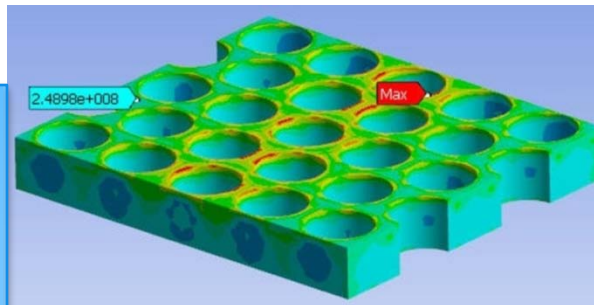
STRUCTURAL ANALYSIS RESULTS OF THE FW ARMOR (1 MM FS LAYER)

D: Static Structural (ANSYS)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1

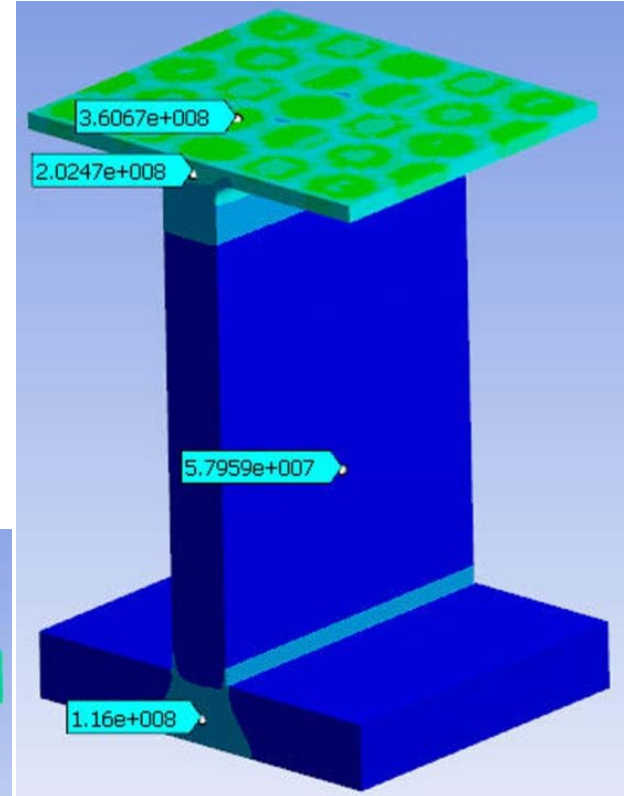
6.9352e8 Max
6.1718e8
5.4085e8
4.6452e8
3.8818e8
3.1185e8
2.3552e8
1.5918e8
8.2848e7
6.5146e6 Min



$\sigma_{p+s}(W)=476 \text{ MPa}$
(3 Sm= $\sim 920 \text{ MPa}$ at
 $T=560 \text{ }^{\circ}\text{C}$)



$\sigma_{p+s}(\text{ODS})=694 \text{ MPa}$
(3Sm=1380 MPa for
ODS 12YWT , and 442 MPa
for F82H at $T= 550 \text{ }^{\circ}\text{C}$)



$\sigma_{p+s}(\text{FS})=361 \text{ MPa}$
(3Sm= $\sim 386 \text{ MPa}$ for
FS at $T= 512 \text{ }^{\circ}\text{C}$)

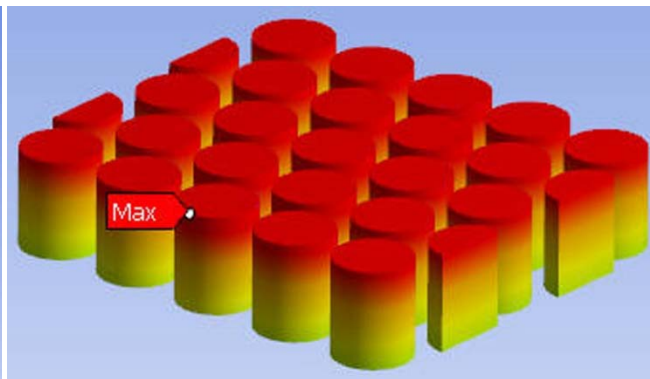
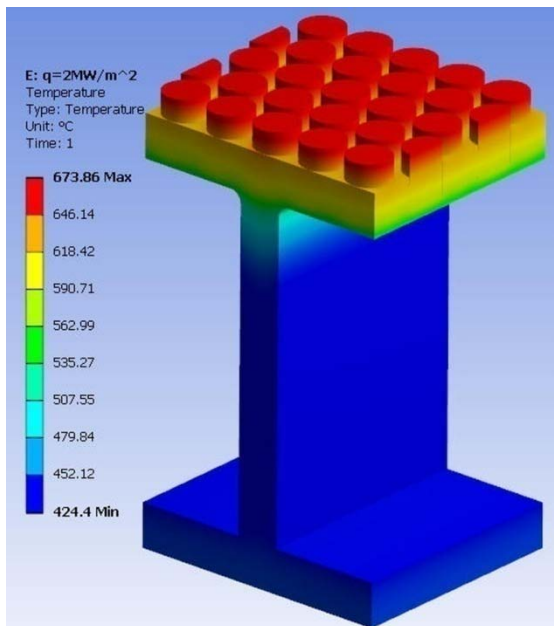
➤ Stress results indicate that the FW armor concept meets the 3 Sm design criteria for a heat flux of 1 MW/m^2 during steady-state operation.

HEAT TRANSFER COEFFICIENT FOR A TRANSIENT HEAT FLUX UP TO 2 MW/M²

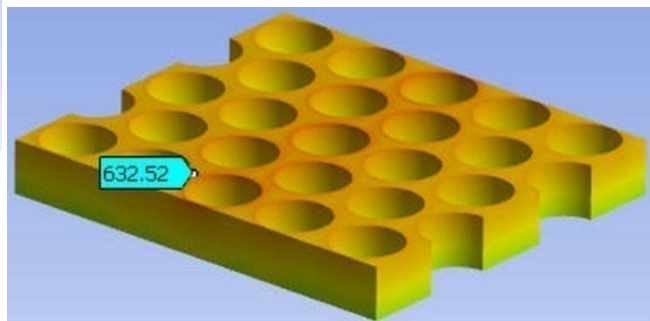
- A value of HTC (Heat transfer coefficient) for the heat flux of 1 MW/m² was required to increase by ~24% comparing to the ARIES-CS FW ($q=0.76$ MW/m²) in order to meet the goal of the material limits on temperature and 3 Sm.
- The increases of the HTC lead to an increase of the pressure drop by ~70%. This should not be a problem if this increase is only 20% of the FW region, but would cause considerable lower power cycle efficiency if the FW armor improved cooling was applied entire FW region.
- For a short transient heat flux up to 2 MW/m², a higher HTC may be required to maintain the temperature of the ODS and FS layers under design limits because it is a mandatory that such transients do not require the FW exchange. However the increase of the HTC would lead to further increase the pressure drop of the FW.
- Determination of the HTC needs an iterations of the elastic steady-state and inelastic transient structural analyses, and plastic material models should be included in ANSYS structural model.

STEADY-STATE THERMAL RESULTS FOR A TRANSIENT HEAT FLUX UP TO 2 MW/M²

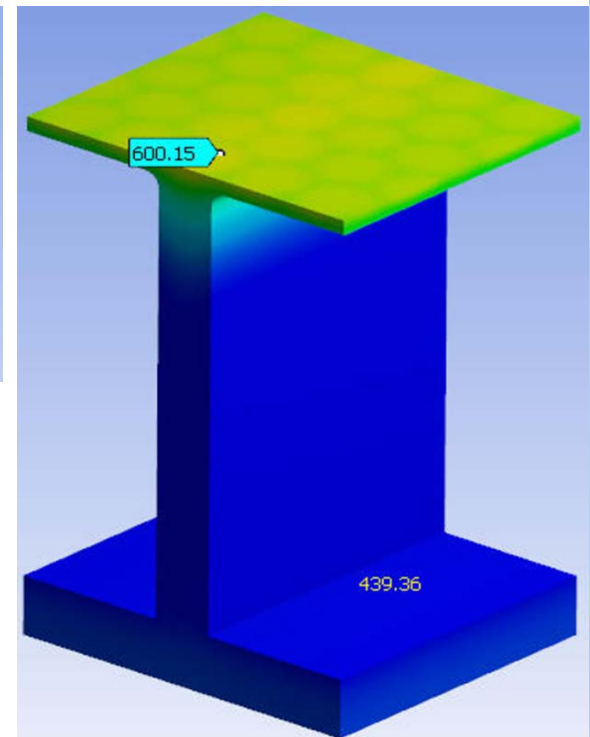
- The goal for the fast transients is to maintain the FS below 600 °C and the ODS below 700 °C with the steady-state calculation.
- A value of HTC for the normal operation (1 MW/m²) is assumed for cooling the FW armor during a short transients with the heat flux up to 2 MW/m².



$T_{\max} (W)=673 \text{ }^{\circ}\text{C} (<1300 \text{ }^{\circ}\text{C})$

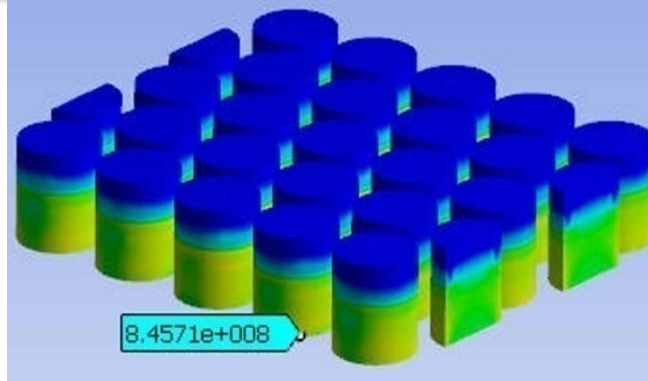
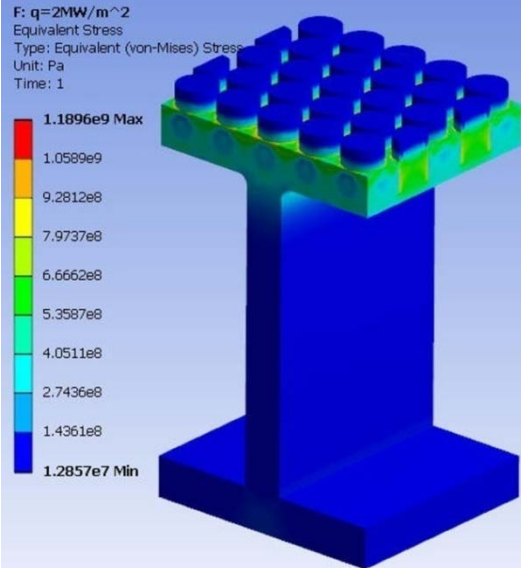


$T_{\max} (\text{ODS})=633 \text{ }^{\circ}\text{C} (<700 \text{ }^{\circ}\text{C})$

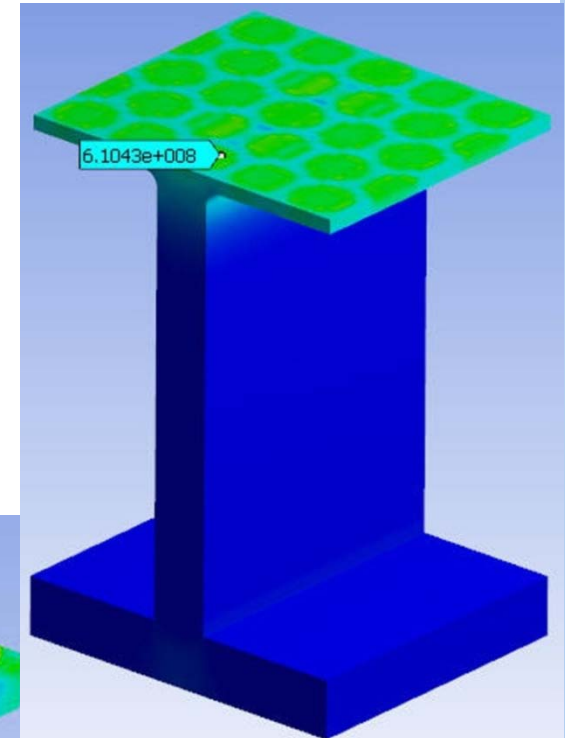


$T_{\max} (\text{FS})=600 \text{ }^{\circ}\text{C} (>550 \text{ }^{\circ}\text{C} \text{ for normal long operation})$

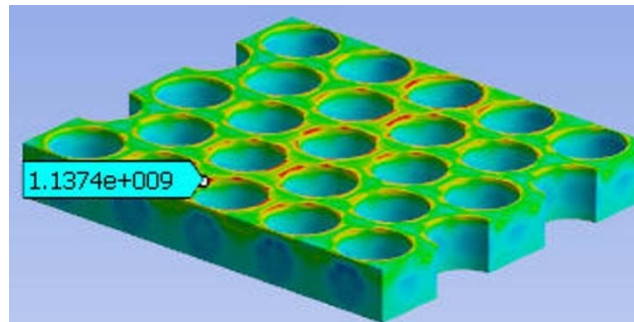
ELASTIC STRUCTURAL RESULTS FOR TRANSIENT HEAT FLUX UP TO 2 MW/M²



$\sigma_{p+s}(W)=846 \text{ MPa}$
(3 Sm= $\sim 794 \text{ MPa}$ at $T=700 \text{ }^{\circ}\text{C}$)



$\sigma_{p+s}(FS)=610 \text{ MPa}$
(3Sm= $\sim 303 \text{ MPa}$ for
FS at $T= 600 \text{ }^{\circ}\text{C}$)



$\sigma_{p+s}(ODS)=1137 \text{ MPa}$
(3Sm=660 MPa for
ODS 12YWT , and 354 MPa
for F82H at $T= 650 \text{ }^{\circ}\text{C}$)

➤ Results confirmed that the stresses of the FW armor exceed the yield strength during transients. More sophisticated analysis of plastic strains should be performed.

SUMMARY AND CONCLUSIONS

- A steady-state thermal and structural analysis of the first wall armor concept has been performed in order to optimize the geometry of FW and confirm the design.
- Results indicate that both the temperature and stresses of FW armor (W-pins, ODS and FS layers) stay within the material limits for a normal operation with the heat flux of 1 MW/m^2 .
- However, sophisticated nonlinear transient analyses need to be performed to investigate nonlinear structural behaviors of the FW armor in order to optimize the design and to prove its viability, such as to calculate the plastic strains and plastic deformation for different scenarios:
 - ✓ During the fabrication steps of the FW armor
 - ✓ During anticipated short transients with the heat fluxes up to 2 MW/m^2
 - ✓ During the operation of the plant, such as the plant start-up and off-power situations

