Update on the FW Armor Design and Inelastic Analyses

X.R. Wang[1], S. Malang[2], and M. S. Tillack[1]

[1]University of California, San Diego, CA
[2]Fusion Nuclear Technology Consulting, Germany

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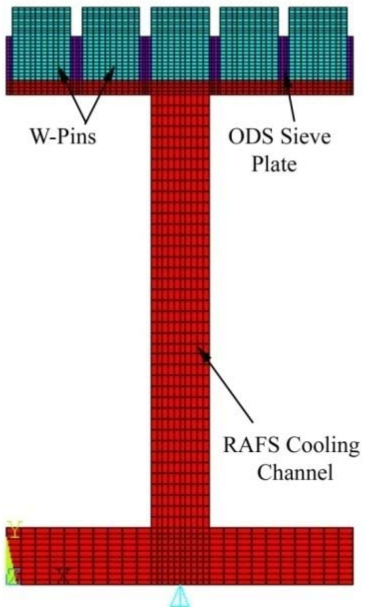
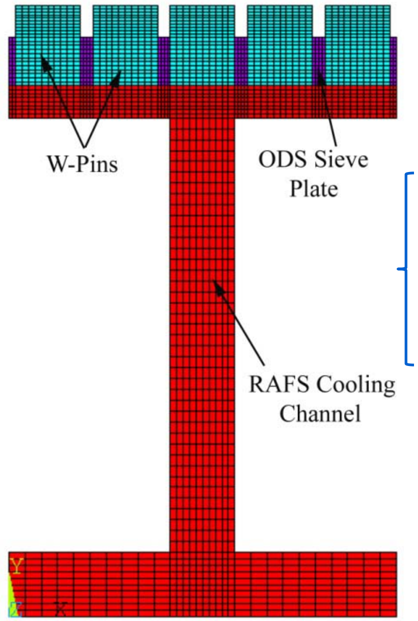
Update on the FW Armor Geometry





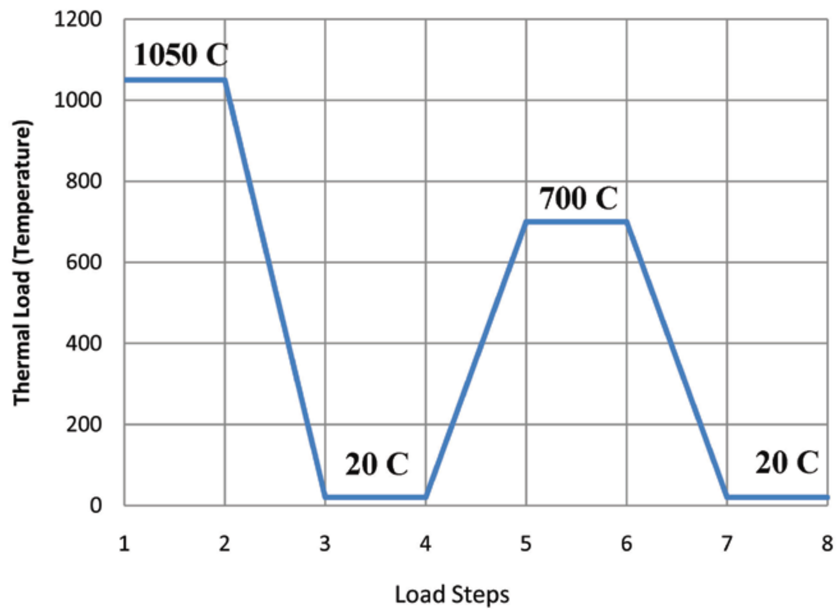
Primary stress ↓

Temperature ↑

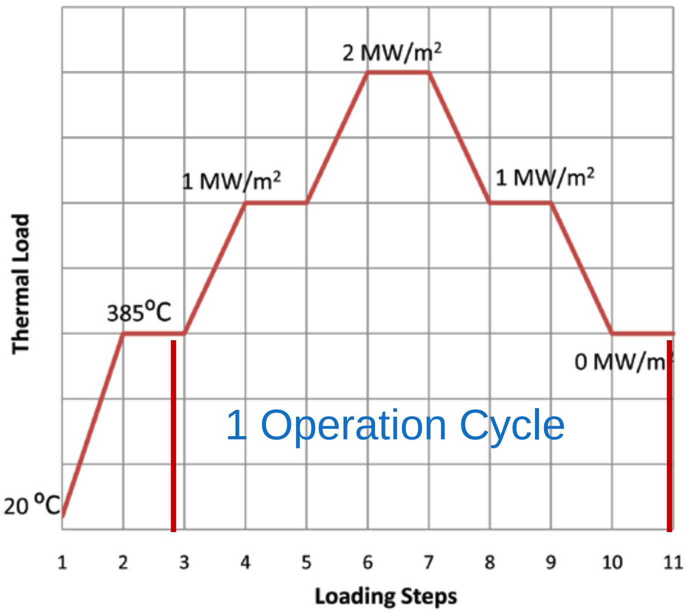
Thermal stresses ↑

- Thickness of the RAFS front-plate is increased from 1 mm to 2 mm
  - 1 mm front plate may be unrealistic for fabrication
  - 2 mm front plate can reduce the primary stress and plastic deformation and avoid ratcheting during transient operation
- Cooling channel is reduced from 30 mm to 27 mm in order to maintain as the same as the nominal FW (38 mm)

Loading Profiles for Fabrication Steps and Transient Operations Are the Same



Loading profile for the fabrication steps and heat treatment



Loading profile for a operation with warm shut-down

➢SFT=1050 ºC (most conservative), mechanical boundary conditions are the same as the case with I mm thick front plate .

✓All the ANSYS plastic material models are rate-independent except thermal creep, therefore, changing slopes of the temperature and heat flux curves will not change the results. The thermal creep is not included yet.

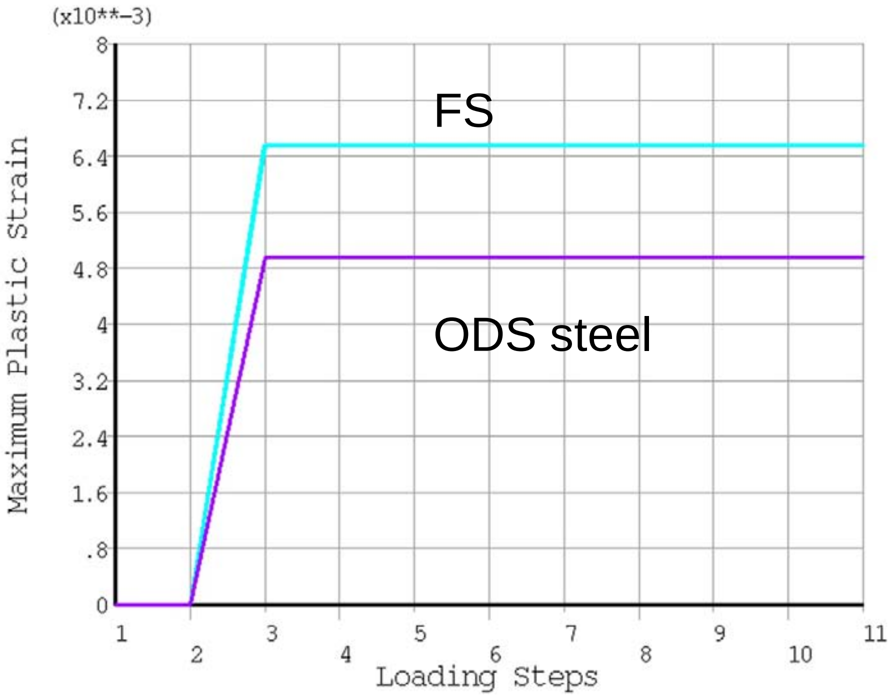
Results Indicate the FW Meets Plastic Strain Limit for Fabrication

- Allowable plastic strain for F82H is ~2.4% at RT and ~1.0% at 700 °C.

- Allowable plastic strain for ODS-EUROFER is ~2.3% at RT and 1.9% at 550 °C, and 2.4% at 700 °C.

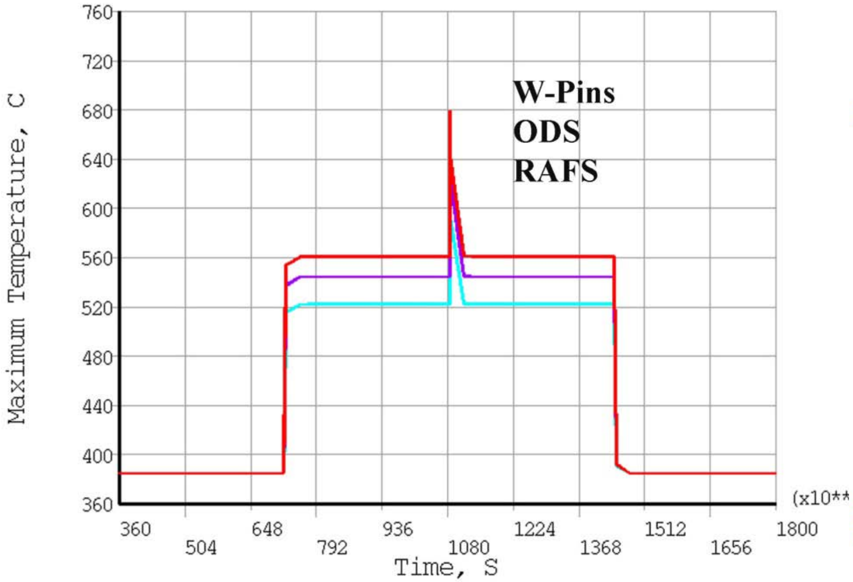
- Allowable plastic strain for pure W is ~0.8% at T=270 °C and 1.0% at T=1200 °C.

- The max. plastic strains are reached at the room temperature, therefore, they are far less than allowable plastic strains.
  - ✓F82H: ε_{pl}= 0.65% (ε_{allow}=2.4% at RT)
  - ✓ODS: ε_{pl}= 0.5% (ε_{allow}=2.3% at RT)
  - ✓W: ε_{pl}= 0.%
  - ✓W elastic strain ε_{el}= 0.26%

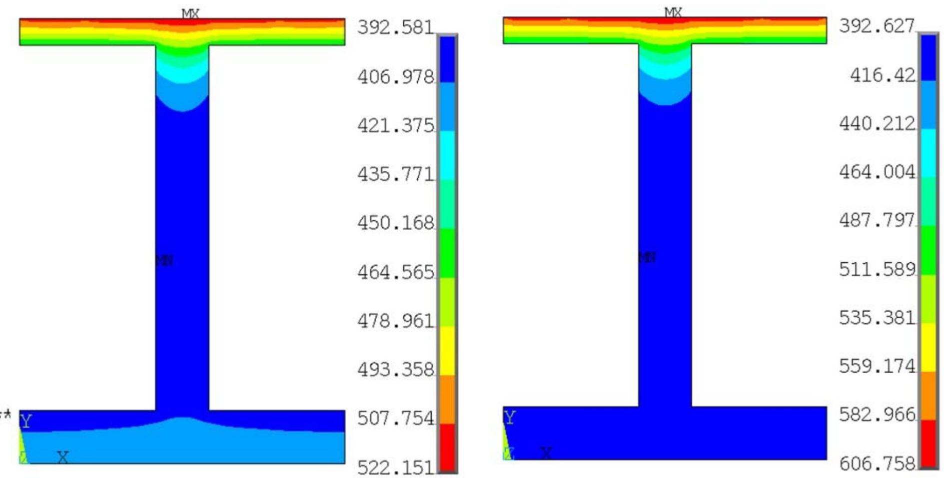


Fabrication steps

Material Temperature Limits Are Met During Transient Operations



q"=1 MW/m²   q"=2 MW/m²



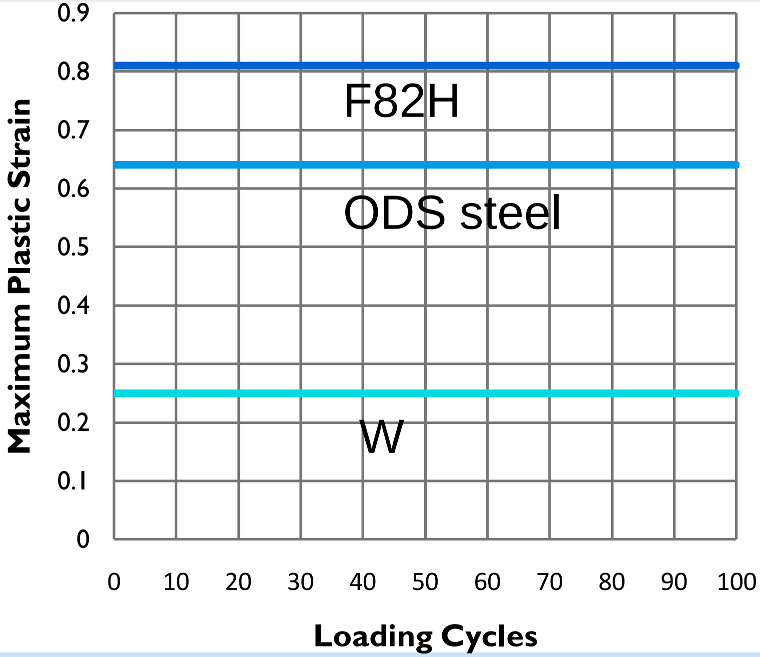
➢Heat transfer coefficient was scaled from ARIES-CS FW design (q"=0.76 MW/m²), and results indicate that temperature limits are met.

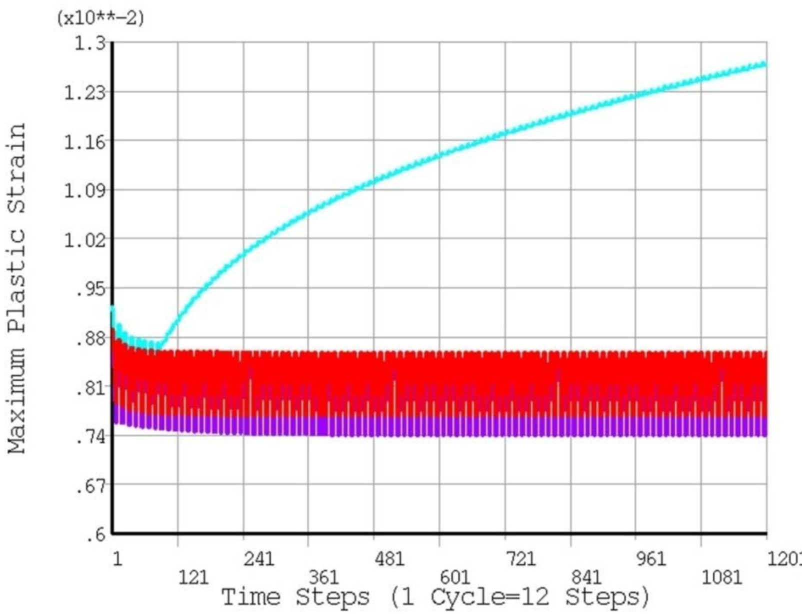
- ✓T_{max} (W)=560°C/680 °C for the heat flux 1.0 / 2.0 MW/m²
- ✓T_{max} (ODS)=544 °C/648 °C (T_{allow}=700 °C)
- ✓T_{max} (RAFS)=522 °C/607 °C (T_{allow}=550 °C)

➢550 °C was set to limit creep for RAFS, but the creep is not concern for the fast transients.

➢Temperature of the W is much lower than 800 °C limit, and the W-pins can become brittle. However, the brittle is not concern because there is no plastic deformations at the very beginning of the lifetime.

No Ratcheting During Transient Operations with Warm and Cold Shutdowns





(results for 1 mm thick FS front-plate)

- ➢The plastic strains are identical for the operations with warm and cold shutdowns.
- ➢The plastic strains reach saturation at the first load step (at T=20 ºC) and no ratcheting.
- ➢The plastic strains of the ODS steel and F82H are less than allowable strains at the corresponding temperature after 100 operation cycles.

- ➢ Ratcheting occurs during operation with cold shutdown.

Thermo-Mechanical Re-evaluation of the Nominal FW Design (ARIES-CS DCLL)

➢ ARIES-CS FW features and parameters

- ✓ 3 mm ODS-steel plate on the top of 1 mm RAFS plate
- ✓ 29 mm cooling channel and 4 mm bake plate
- ✓ 38 mm for total FW thickness
- ✓ Operation pressure P=10 MPa
- ✓ Surface heat flux q''=0.76 MW/m^2 and q'''=44 MW/m^3
- ✓ Heat transfer coefficient in the front cooling interface, h.t.c=8825 W/m^2-K
- ✓ He inlet/outlet temperature in the FW, Tinl/Tout=385/430 ^{o}C

➢ ARIES-CS FW/blanket results and performance:

- ✓Gross power cycle efficiency =43%
- ✓Max. ODS temperature=642 C(<700 ^{o}C)
- ✓Max. RAFS temperature=546 C(<550 ^{o}C)
- ✓Max. combined primary and secondary stresses at ODS σ=654 MPa (3Sm=660 MPa at 650 ^{o}C)
- ✓Max. combined primary and secondary stresses at RAFS σ=390 MPa (3Sm=354 MPa at 550 ^{o}C)

➢ **The temperature of the RAFS is very close to the limit, and stresses are above the design limits based on thermal and an elastic analysis.**

➢**1 mm RAFS is changed to 2 mm for fabrication reason.**

➢**Re-evaluation of the nominal FW will be based on the elastic-plastic analyses, allowing local yielding, considering plasticity, ratcheting and shakedown.**

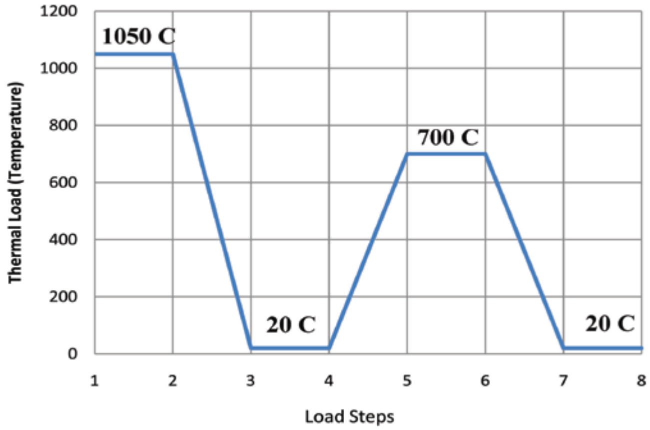
Re-evaluation of the Nominal FW Design (ARIES-CS DCLL)

➢The goal is to determine how high the heat flux can be without failure.

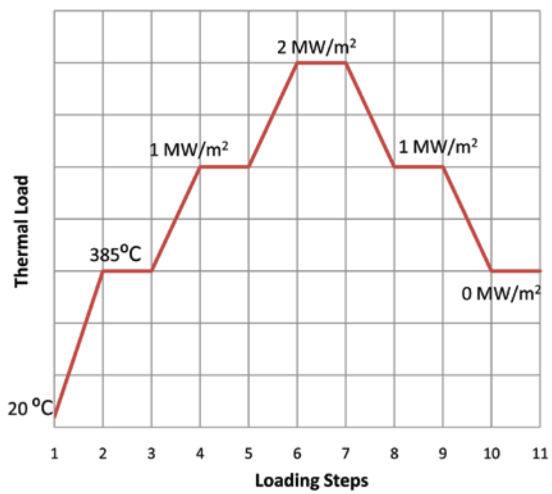
➢In thermal modeling, all the cooling conditions and heat transfer coefficient are the same as that of the FW with W armor.

➢In structural modeling, the plasticity is added, and ANSYS element type, plastic material models, thermal and structural loadings, and mechanical boundaries are the same.

➢All the material properties are assumed to be the temperature-dependent.



Fabrication steps

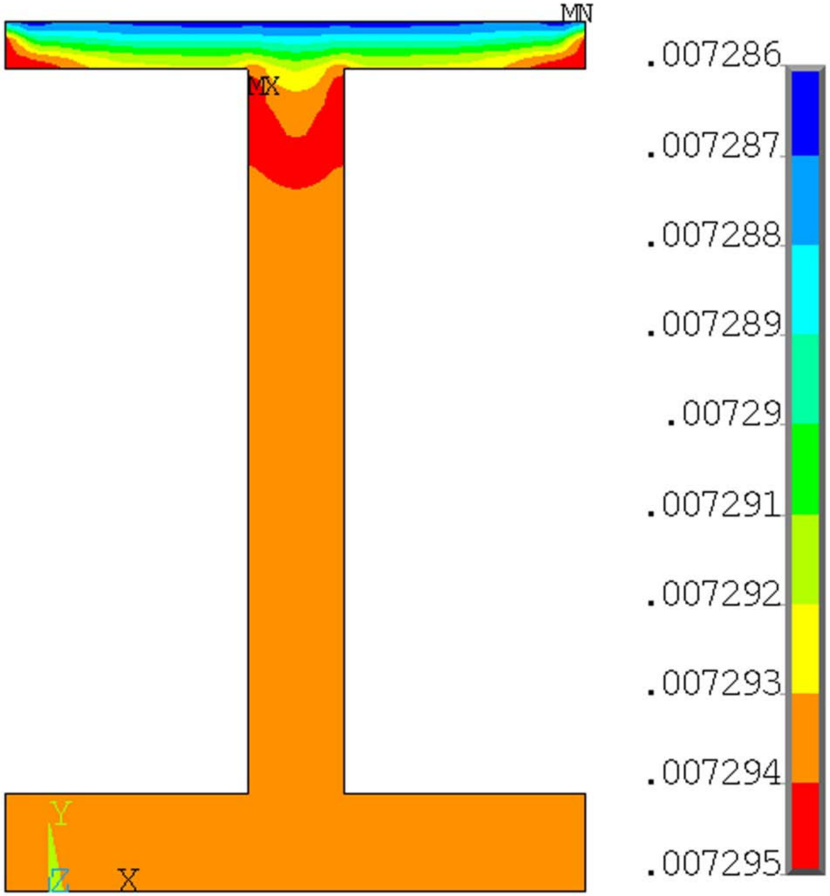


Operation cycle

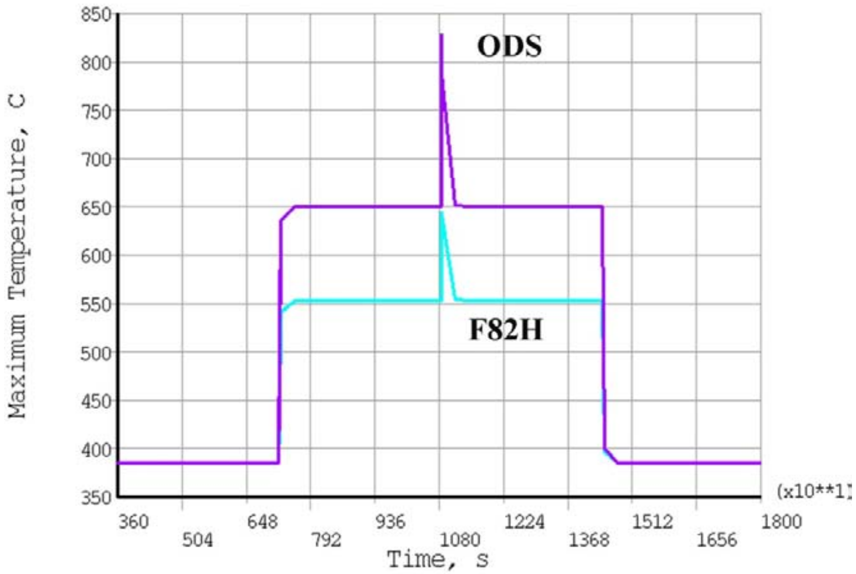
Results for Fabrication Steps (Nominal FW)

- The max. plastic strains are ~0.73% for F82H, and 0.48% for the ODS steel at the RT (allowable plastic strains at the RT, ε_{allow} =2.4% for F82H and 2.3% for ODS steel).

- Both strains of the ODS steel and F82H stay within allowable plastic strain limits of the corresponding temperature

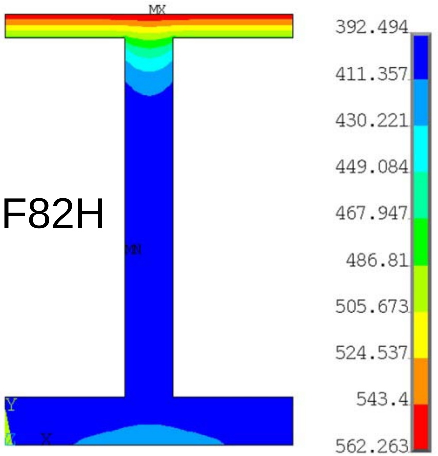


THERMAL RESULTS DURING THE TRANSIENT OPERATIONS (NOMINAL FW)



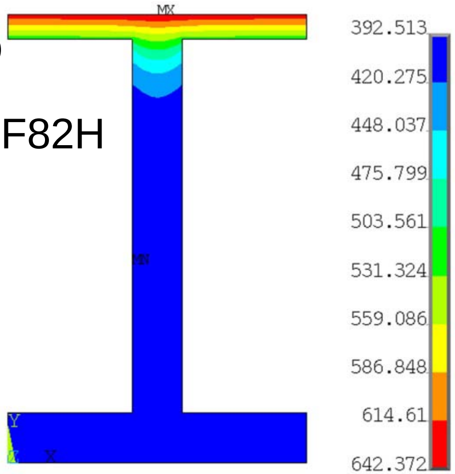
q''=1 MW/m^2

F82H



q''=2 MW/m^2

F82H



- Material temperature:
  - ✓T $_{max}$ (ODS)=650 ºC/826 ºC (T$_{allow}$=700 ºC) for the heat flux 1.0 / 2.0 MW/m^2
  - ✓T $_{max}$ (RAFS)=562 ºC/642 ºC (T$_{allow}$=550 ºC)

- Max. temperature of the F82H is above the temperature limits at the heat flux of 1 MW/m^2 and 2 MW/m^2, and the temperature of ODS steel exceeds temperature limit at 2 MW/m^2.

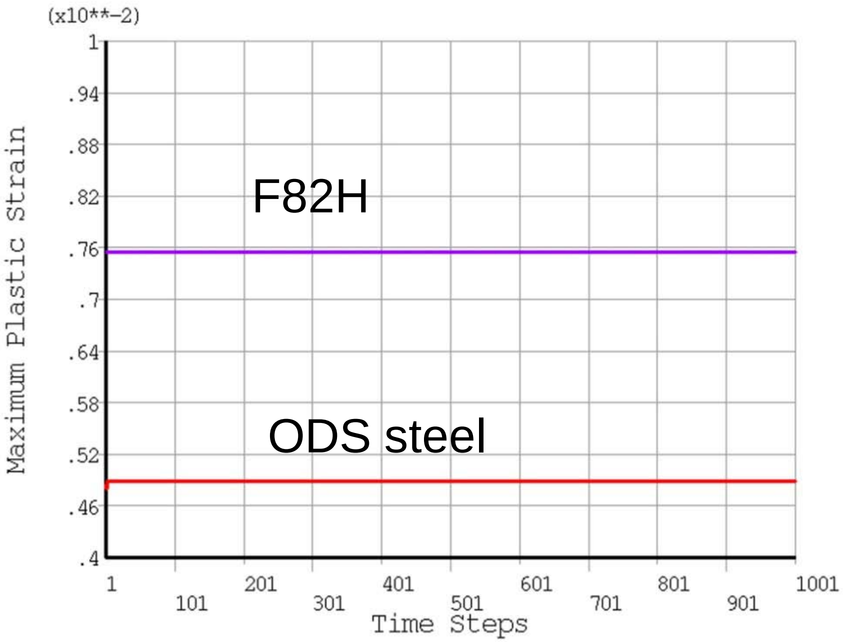
Plastic Strains During the Transient Operations (Nominal FW)

➢The max. plastic strains are ~0.76% for F82H and 0.49% for ODS steel at the RT.

➢The plastic strains for both F82H and ODS steel reach saturation at the RT in the first operation load cycle.

➢The plastic strains show that the nominal FW may accommodate a heat flux up to 2 MW/m^2 without exceeding the plastic strain limit.

➢However, the temperature of the F82H already exceeds the temperature limit at both 1 .0 MW/m^2, and the ODS steel is also above the limit at 2.0 MW/m^2.



100 operation cycles

Comparing Results Between Elastic and Plastic Analyses (Nominal FW)

- **Plastic Deformation Analyses** allow local yielding, and consider plasticity, ratcheting and shakedown.
- **Elastic Analyses** limit the analysis to the elastic behavior, and the ASME 3 Sm limit is used for the sum of primary + secondary stresses.
- Thermo-coupled stress calculations are based on stress-free-temperature of 1050 ºC.

Heat Flux	Plastic Analyses		Elastic Analyses	
	Stress of ODS steel, MPa	Stress of F82H, MPa	Stress of ODS steel, MPa	Stress of F82H, MPa
0.0 MW/m^2	483	370	1530	1520
1.0 MW/m^2	231	202	1140	1500
2.0 MW/m^2	315	271	1520	1510

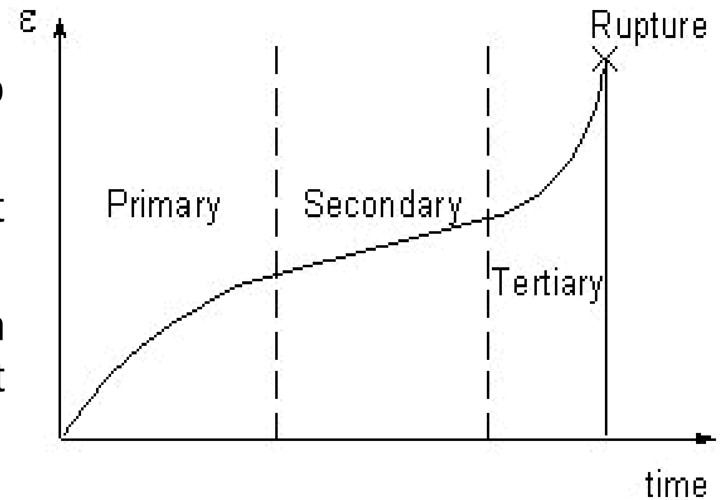
Lesson on ANSYS Creep Model

➢Creep means a time dependent deformation of a material under thermal stresses or applied load. Thermal stresses will be reduced by the creep (**stress relaxation**).

➢ANSYS has the capability of modeling the first two stages (primary and secondary).

➢The tertiary stage is usually not analyzed since it implies impending failure (gross element distortion).

➢ANSYS analyzes creep using two time integration methods. Both are applicable to static or transient analyses.



- ❑***Implicit*** creep method is robust, fast, accurate, and recommended for general use.
  - ▪ *Handles temperature dependent creep constants, as well as simultaneous coupling with isotropic hardening plasticity models.*
- ❑***Explicit*** creep method is useful for cases where very small time steps are required.
  - ▪ Creep constants cannot be dependent on temperature.
  - ▪ Coupling with other plastic models is available by superposition only.

ANSYS Implicit Creep Models

- There are 13 ANSYS built-in creep models, 8 for primary stage, 3 for secondary stage and 2 for combined primary and secondary models. For example,

  1. Strain Hardening: $d\varepsilon_{cr} /dt = C1\sigma^{C2}\varepsilon_{cr}^{C3}e^{-C4/T}$ (4 creep constants, C1>0)
  2. Time Hardening: $d\varepsilon_{cr}/dt = C1\sigma^{C2}t^{C3}e^{-C4/T}$ (4 creep constants, C1>0)
  3. ……………

  7. Modified Strain Hardening: $d\varepsilon_{cr}/dt = \{C1\sigma^{C2}[(C3+1)\ \varepsilon_{cr}]^{C3}\}^{1/(C3+1)}e^{-C4/T}$
  8. Generalized Garofalo: $d\varepsilon_{cr} /dt = C1[\mathrm{Sinh}(C2\sigma)]^{C3}e^{-C4/T}$(4 creep constants, C1>0)
  9. ……………………..
  10. Norton: $d\varepsilon_{cr} /dt = C1\sigma^{C2}e^{-C3/T}$ (3 creep constants, C1>0)
  11. Time Hardening: $\varepsilon_{cr} = C1\sigma^{C2}t^{C3+1}e^{-C4/T}/(C3+1)+C5\ \sigma^{C6}te^{-C7/T}$
  (7 creep constants, C1>0, C5>0)
  12.………………………
  13. Generalized Time Hardening for primary stage

- **Norton creep model (Model #10)** is most popular one used in industries for the secondary stage.
- For creep simulation, the user needs to specify the creep model and creep constants of each model in ANSYS input.
- The temperature-dependent creep constants are given by experimental creep test data.
- There is no much reliable creep data available for the ODS steel.

Creep Modeling for the FW Armor

➢Temperature of the W-pins is ~ 680 ºC, therefore, thermal creep is not important as a deformation mechanism. W thermal creep begins to become significant around 1500 ºC and above.

➢Experiments shown the creep strength of “normal” ODS steel is much higher than for the FS itself. “Advanced” ODS steels have an even higher creep strength. For this reason, the creep of ODS steel is ignored considering the relatively low temperature during operation.

➢ANSYS Norton creep model is selected, and the creep constants for F82H are from FZK reports (2003).

➢Norton creep equation:

$$d\varepsilon_{cr}/dt = C1\sigma^{C2}e^{-C3/T} \text{ (1/hour)}$$

➢No creep results have been obtained so far.

➢The creep analyses will be continued.

Creep Constants based on Creep Test at FZK

	C1	C2	C3	Stress, MPa
450 ºC	2.0E-67	29	0.0	360-320
500 ºC	7.0E-60	23	0.0	300-230
550 ºC	1.0E-45	18	0.0	260-170
600 ºC	3.0E-25	12.5	0.0	160-100
650 ºC	5.0E-16	8.4	0.0	90-50

Summary

➢Modifications of the FW armor design have been made for fabrication reason and reducing the primary stress.

➢The results indicate that the FW with W-pins meets the high temperature limit and the plastic strain limit at the heat flux up to 2 MW/m^2 during fabrication and transient operations with warm and cold shutdown scenarios.

➢The nominal FW design (ARIES-CS) has been re-evaluated based on the thermal and plastic analyses, and the results show the temperature of the F82H is above the limit at 1 MW/m^2. However, the structural behaviors stay within the plastic limits at the surface heat flux up to 2 MW/m^2.

➢The creep analyses will be continued.