DESIGN AND ANALYSIS OF AN INNOVATIVE FIRST WALL CONCEPT FOR ARIES

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PROBLEMS OF FW DESIGN FOR FUSION POWER PLANT

- FW is usually designed for a steady-state heat flux $q'' < 1 \text{ MW/m}^2$ in order to meet the design criteria, such as
  - Material temperature limits: minimum temperature for avoiding embrittlement, and maximum for thermal creep strength
  - Material stress limits: ASME code requires the sum of primary + secondary stresses < 3 Sm, and the structure in elastic regime.
  - Pumping power: pumping power < 3-5% of the removed thermal power.

- In ARIES-CS and ARIES-RS power plant studies, the temperature and stresses are close to the limits for the selected RAFS as structural material and He as coolant with operation pressure of 8 MPa, and $q'' < 1 \text{ MW/m}^2$.

- However, there are indications that at some locations a fast increase of the surface heat flux up to ~ 2 MW/m$^2$ can occur, accompanied by much higher erosions.

- It is mandatory that such transients do not require a FW exchange, because this could lower the availability of the plant to intolerable values.
NEW FW ARMOR CONCEPT FOR FUSION POWER PLANT

New FW armor has been proposed by Siegfried Malang for ARIES power plant:

- FW armor is composed of brush-like W-pins embedded in a thin plate of ODS steel.
- The armor will be arranged at the anticipated locations where the FW may subject large transient heat fluxes.
- A similar solution had been developed for the ITER divertor target plates, where W-pins are embedded in a copper heat sink.
  - Micro brush with a diameter of 1 ~ 4 mm
- We are trying to extrapolate these ideas to the conditions at the FW, requiring a combination of W and ODS-steel for transient heat fluxes up to 2 MW/m².
NEW FW ARMOR CONCEPT FOR FUSION POWER PLANT (CONT.)

- Design goals are to accommodate a heat flux of 1 MW/m$^2$ during a normal operation and up to 2 MW/m$^2$ at transient events.
- With the FW armor concept, ~65% of total FW armor surface area would be covered by W, and ~35% by ODS steel. The effective conductivity of the first wall layer will be increased to ~75 W/m$\cdot$K (~33 W/m$\cdot$K for ODS), reducing temperature gradient and thermal stresses.
- There are ~80% with normal FW and normal cooling and other regions (~20%) with added FW armor and much larger heat transfer coefficient.
Main Issues to be Considered for Design of Such a FW Armor

- Issues
  - *Decrease of the tritium breeding rate by the additional material*
  - *Increase of the FW temperature*
  - *Increase of the FW thermal stresses and the stresses exceeding elastic regime*

- Clearly, TBR must not be reduced by more than one percent

- Temperature limits to be considered for the RAFS and ODS
  - $T_{\text{min}} > 350 \, ^\circ\text{C}$ to avoid embrittlement for RAFS
  - $T_{\text{max}} < 550 \, ^\circ\text{C}$ for creep strength reasons for RAFS
  - $T_{\text{max}} < 650 \, ^\circ\text{C}$ for standard ODS
  - $T_{\text{max}} < 750 \, ^\circ\text{C}$ for advanced ODS steels with nano-sized particles.

- Stress limits allowing a simple analysis based on elastic deformation only:
  - Primary (pressure) stresses < $S_m = \text{Min}(1/3 \text{ of rupture strength, } 2/3 \text{ of yield strength})$
  - Sum of primary+ secondary (thermal) stresses < $3 \, S_m$
SUGGESTED FW FABRICATION METHOD

- Fabricate the FW cooling panel by HIPing (Hot Isostatic Pressing) 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). At this high temperature and long time, any fabrication stresses will be released.
- Cool the assembly down to the room temperature. 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 in ODS and 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.
SUGGESTED FW FABRICATION METHOD (CONT.)

Bracing the W-pins, ODS plate and FS cooling channel together at temperature of 1000~1100ºC.
“Design by Code”
The simplest method which is always the first step is to limit the analysis to the elastic behavior of the structural material. If the calculated sum of primary and secondary stresses remains $< 3 \text{ Sm}$, the design is fine.

“Design by Analysis”
However, it is not always possible to avoid plastic strain caused by exceeding the yield strength or by thermal creep. In such cases, the analysis has to show that the strain does not continuously increase with the number of temperature cycles (“ratcheting”) but reaches its final value after a few cycles (“shakedown”).

“Design by Experiments”
As a third method allowed by the ASME code, it is possible to “design by experiments”, requiring an extensive test program to prove that the component will survive all anticipated transients.

With our suggested FW armor, we will go to the method 2, performing sophisticated analyses of plastic strains.
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.
  \[ \varepsilon_{pl} < \varepsilon_{allow} \]
  \( \varepsilon_{pl} \): Maximum value of the principal strains
  \( \varepsilon_{allow} \): 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:
    “The ratcheting is a progressive incremental inelastic deformation or strain which can occur in a component that is subjected to variations of mechanical stress, thermal stress, or both”
  - Behavior of Ratcheting:
    - Unlimited continuation -> failure of the component
    - Ceased ratcheting -> plastic shakedown

PLASTIC STRAINS DURING THE FW FABRICATION STEPS

- Large mismatch of thermal expansion coefficient between W and ODS/or RAFS causes high thermal stresses during the FW panel fabrication.
- ANSYS elastic-inelastic model:
  - Bilinear Isotropic Hardening Material Model
  - Linear elastic, ideal plastic without hardening and thermal creep
  - Stress-free temperature assumed to be 1050 °C (Brazing temperature)
  - No mechanical constrains during fabrication steps
  - Starting from 1050 °C; uniformly cooling down to RT uniformly heating up to 700 °C (tempering temperature); cooling down to RT.

ANSYS Bilinear Isotropic Hardening Model:
“This option uses the von Mises yield criteria coupled with an isotropic work hardening assumption. This option is often preferred for large strain analysis.”
PLASTIC STRAINS AT THE BRAZING INTERFACE OF THE F82H SIDE

- At point-3, the max. plastic strain $\varepsilon_{pl} = 0.85\% (< \varepsilon_{allow} = 1.1\%)$*
- It is also less than the minimum plastic strain at rupture for F82H, $\varepsilon_{tr}=1\%$ ($\varepsilon_{tr} = \ln(100/100-%RA))^{**}$
  
  $\varepsilon_{tr}$ is min. true strain at rupture, %RA is reduction area at rupture from tension test.


At point-4, the max. plastic strain $\varepsilon_{pl} \sim 0.4\%$.

The plastic strain reaches saturation when the assembly cooling down to RT from brazing temperature.

**Graphical Representation:**

- **Graph Title:** Plastic Strains at the Brazing Interface of the ODS Sieve Plate
- **Axes:**
  - Y-axis: Maximum Plastic Elongation ($\times 10^{-2}$)
  - X-axis: Load Steps
- **Graph Details:**
  - Cooling, Heating, and Cooling phases
  - Points: 1, 2, 3, 4
  - Temperature Markers: 1050°C, 700°C, 20°C

**Diagram Description:**

- **Legend:**
  - Brazing
  - Cooling
  - Heating

**Legend Placement:**

- **Legend Objects:**
  - Points 1, 2, 3, 4
  - Temperature Markers
  - Cooling and Heating Phases
**Example Comparison of Elastic-Plastic Structural Analysis**

**Elastic Structural Analysis**

Stress at RT
\[ \sigma = 2360 \text{ MPa} \]

**Inelastic Structural Analysis**

Stress at RT
\[ \sigma = 1300 \text{ MPa} \]
The goal for the fast transients is to maintain the RAFS (F82H) below 550 °C and the ODS below 700 °C with the steady-state calculation.

A value of HTC for a normal operation (q=1 MW/m²) scaled from ARIES-CS FW design (q=0.76 MW/m²) needs to be doubled for cooling the FW armor during a short transients with the heat flux up to 2 MW/m². HTC of ~2.30x10⁴ W/m²-K was utilized.

The FW components meet the temperature limits.

- $T_{\text{max}}(\text{W})=611 \, ^\circ\text{C} (<1300 \, ^\circ\text{C})$
- $T_{\text{max}}(\text{ODS})=575 \, ^\circ\text{C} (<700 \, ^\circ\text{C})$
- $T_{\text{max}}(\text{RAFS})=541 \, ^\circ\text{C}$

(<550 \, ^\circ\text{C} \text{ for normal long operation})
Elastic analysis confirms that the FW armor assembly stays in the elastic regime for \( q''=1.0 \text{ MW/m}^2 \) during normal operation.

However, both W-Pins and RAFS cooling ducts exceed the elastic regime for the heat flux up to 2 MW/m\(^2\). More sophisticated analysis of plastic strains should be performed.

- Temperature loads
- Internal pressure \( P=10 \text{ MPa} \)
- Symmetry B.C. at both sides
- \( U_y=0 \) at the bottom plane
- SFT=700 °C (tempering temperature)

\[
\sigma_{p+s} (W)=887 \text{ MPa} \\
(3 \text{ Sm}=\sim835 \text{ MPa at } T=650 \degree C)
\]

\[
\sigma_{p+s} (ODS)=600 \text{ MPa} \\
(3 \text{ Sm}=\sim1260 \text{ MPa for advanced ODS 12YWT, 399 MPa for standard ODS at } T=600 \degree C)
\]

\[
\sigma_{p+s} (RAFS)=954 \text{ MPa} \\
(3 \text{ Sm}=\sim354 \text{ MPa for F82H at } T=550 \degree C)
\]
A new FW protection armor based on the successful development of the ITER brush divertor concept has been proposed for the ARIES power plant to allow a fast transient heat flux up to 2 MW/m².

Progress on the elastic-plastic analysis has been made.

The first results of the plastic analysis indicate that the FW assembly meet the plastic criteria during the fabrication.

More sophisticated FE analyses including the description of the plastic deformations during transient operation are underway.