Study of Thermal Requirements in the HFTM using Finite Element and Monte Carlo Simulations

J.M. Palomino Cobo, E. Puertas, R. Palma, R. Gallego

Department of Structural Mechanics, University of Granada

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Outline

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Thermal requirements in the specimens stack

- Control the specimens temperature at defined levels $(250 - 550)^{\circ}C$, depending on the compartment.
- Temperature spread must be within $\pm 3\,\%$ (in $80\,\%$ of the available volume).

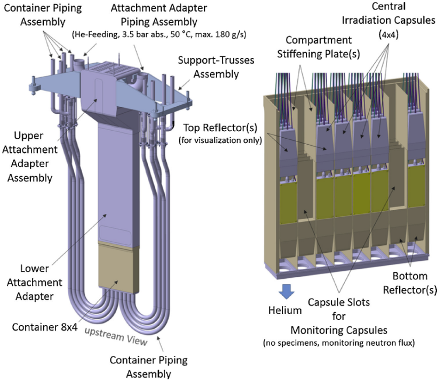

Figure: HFTM design and the container [1].

The homogeneous HFTM specimen stack

- Mix. = 75% Eurofer97 [2] + 25% liquid sodium [3].
- Numerical fitting applied for temperatures between (300-1000) K.

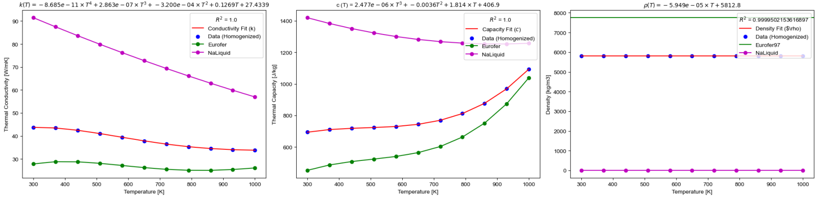

Figure: Thermal properties of the homogenized material.

Finite Element Method (FEM)

- Nuclear heating prescribed from neutronics calculations.
- Non-linearity handled via Newton-Raphson method.
- Time integration: Newmark β method.
- Displacement-based formulation.
- Stationary simulations.
  - Mesh: 1000 eight-noded brick elements.
  - Simulation time: 7.72 seconds on a 3.4 GHz processor with 16 GB RAM.

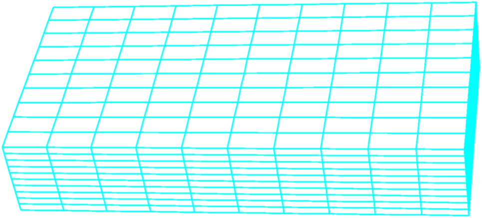

Figure: Mesh of the homogenized Model stack.

Boundary Conditions for one irradiation capsule

- Heaters: Fixed temperature to the reference temperature of the compartment where the rig is located.
- Cooling channels modeled as 2D convection elements:
  - Coolers OFF: $H = 5\,\mathrm{W/m^2/K}$ [1].
  - Coolers ON: $H = 125\,\mathrm{W/m^2/K}$ (MCA).

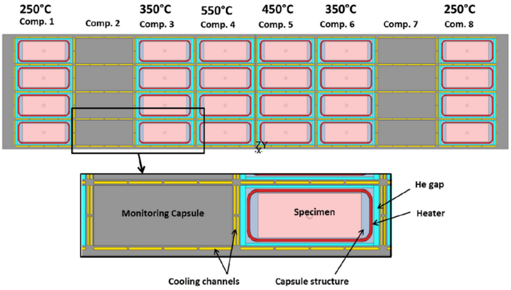

Figure: HFTM design distributions of rigs [1].

2D Radiation/Convection Element

$$q_c = q^p + \underbrace{h(T - T_\infty)}_{q^c} + \underbrace{\epsilon\sigma(T^4 - T_\infty^4)}_{q^r}$$

$$R_{T_A} = -\int_{\Gamma_q} N_A q_c \,\mathrm{d}\Gamma$$

$$K_{\Pi_{AB}} = -\int_{\Gamma_q} N_A (h + 4\epsilon\sigma T^3) N_B \,\mathrm{d}\Gamma$$

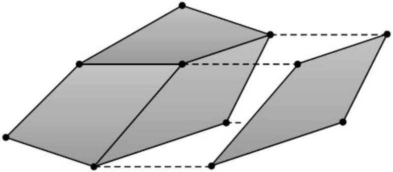

Figure: 2D interfaz element coded.

Reliability Analysis

Objective: To estimate the probability of failure of thermal requirements under uncertain conditions.

Limit state function:

$$g(X) > 0 \leftrightarrow Ok!.$$
$$g(X) \leq 0 \leftrightarrow Fails.$$

Indicator function:

$$\text{I(X)} = \begin{cases} 1 \text{ if } g(X) \leq 0 \\ 0 \text{ otherwise} \end{cases}$$

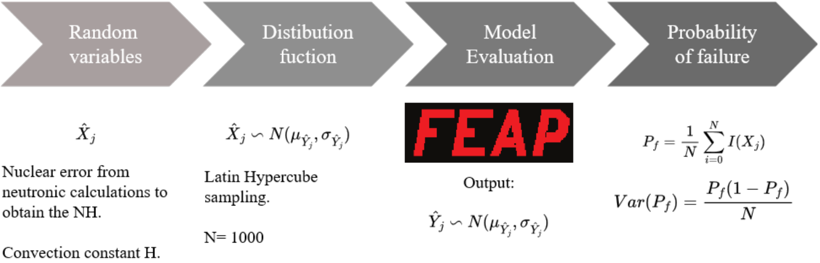

Figure: Flowchart of reliability algoritm

Proposed Probabilistic Metric

- Thermal distribution is treated as a probabilistic variable.

$$\mu_{ref}(t) = \frac{1}{N}\sum_{i=1}^{N} t_i = \frac{1}{N}\sum_{i=1}^{N} \frac{T_i}{T_{ref}} = \frac{\mu(T)}{T_{ref}} \Longrightarrow 1 \qquad (1)$$

$$\sigma_{ref}(t) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(t_i - 1)^2} \qquad (2)$$

- It's not the standard deviation!
- Thermal Requirements of HFTM $\longrightarrow \sigma_{ref}(t) \leq 0.03$.

Results

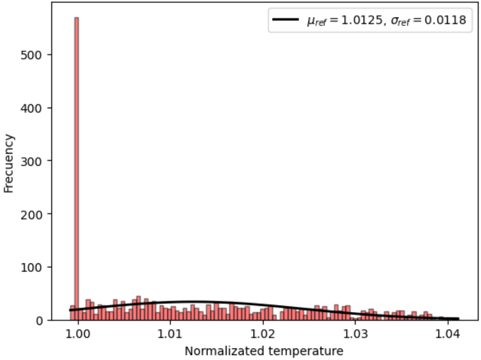

Figure: Uncertainty analysis

- Thermal failure probability: $P_f = 0.3\,\%$.
- Results for N$=$ 1000 iterations.

Conclusions

- Non-linear and probabilistic FE formulation: 3D conduction and 2D convections elements are available for future simulations
- Developed method for reliability analysis
- Thermal probability of failure: $P_f = 0.3\,\%$.
- Future developments:
  - Use the CIC.v2.0 stack model in reability studies
  - Refining boundary conditions
  - Developing a code for thermal stress analysis

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