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MTR PLATES MODELING WITH MAIA

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ABSTRACT

MAIA is a thermo-mechanical code dedicated to the modeling of MTR fuel plates. The main physical phenomena modeled in the code are the cladding oxidation, the interaction between fuel and Al-matrix, the swelling due to fission products and the Al/fuel particles interaction. The creeping of the plate can be modeled in the mechanical calculation.
MAIA has been validated on U-Mo dispersion fuel experiments such as IRIS 1&2 and FUTURE. The results are in rather good agreement with post-irradiation examinations.
MAIA can also be used to calculate in-pile behavior of U_3Si_2 plates as in the SHARE experiment irradiated in the SCK/Mol BR2 reactor.
The main outputs given by MAIA throughout the irradiation are temperatures, cladding oxidation thickness, interaction thickness, volume fraction of meat constituents, swelling, displacements, strains and stresses.
MAIA is originally a two-dimensional code but a three-dimensional version is currently under development.

1. Introduction

MAIA is a 2D thermo-mechanical code developed by CEA to model MTR dispersion fuel plates' behavior. The main goal of MAIA is to evaluate the thermal conditions and the mechanical behavior of experimental plates during irradiation and thus to help to interpret irradiation experiments of these MTR plates. Other purposes of the code are to perform parametric studies to identify the more sensible input parameters on plates' behavior and to be a support to the design of the future CEA "Jules Horowitz Reactor" (JHR).
The MAIA 2.0 version has been developed within the PLEIADES platform used for CEA fuel codes [1].

This paper presents main aspects of modeling, code validation for U-Mo fuels, some results of the code illustrated with the IRIS 2 experiment and finally 3D developments.

2. Modeling

Geometry of the modeled plates is either plane or curved. Meat (in red in Figure 1 and Figure 2, cladding in blue) is treated as homogeneous for the thermal and mechanical resolution with a Finite Element Method (FEM).

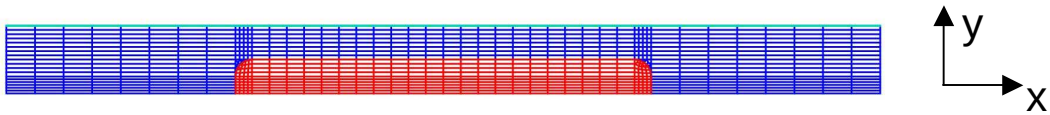

Figure 1: Mesh of plane plate (half plate)

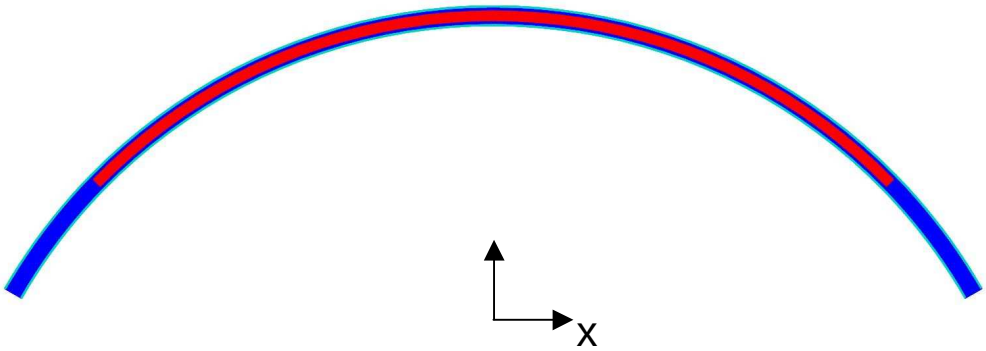

Figure 2: Mesh of curved plate

The code is at present dedicated to dispersion fuel plates: U-Mo or U_3Si_2 fuel particles dispersed in aluminum A5 matrix for the meat and cladding among AG3, AlFeNi or 6061 Al alloys.
The meat thermal conductivity is homogenized using an auto-coherent model:

$$k_{100}=\frac{-k_f+3V_f k_f+2k_m-3V_f k_m+\sqrt{8k_f k_m+\left(k_f-3V_f k_f-2k_m+3V_f k_m\right)^2}}{4} \qquad (1)$$

where k_{100} is the thermal conductivity of the fully dense meat, k_f is the thermal conductivity of the fuel particles with interaction layer, k_m is the thermal conductivity of the matrix and V_f is the volume fraction of the fissile particles (fuel and interaction phase) [2].
A model evaluates the external cladding oxidation, inducing a rise of temperatures in the plate.
The PF fuel swelling model uses a linear slope of 6.2 % per unit fission density in the particle (10^{27} f/m^3) for U_3Si_2 [3] and 6.3 % for U-Mo. The slope for U-Mo has been adjusted to fit with French irradiation experiments (cf. Figure 3).

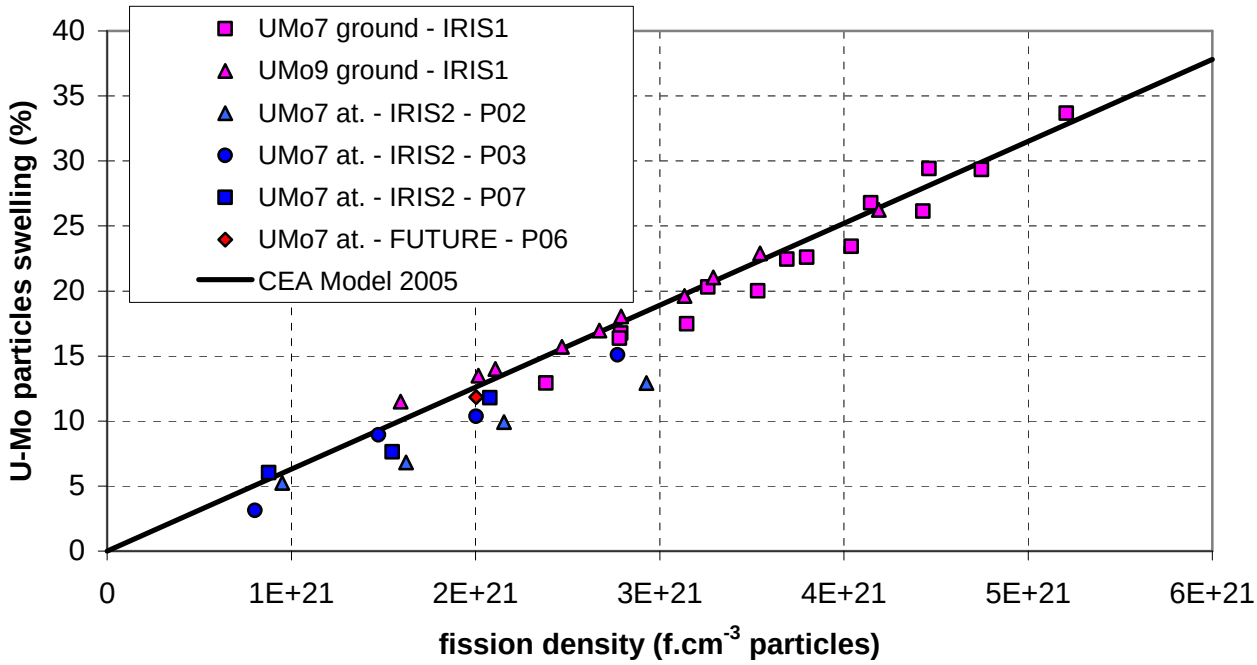

Figure 3: CEA model for meat swelling

The fuel-matrix interaction thickness correlation used in MAIA for U-Mo fuels is classically an Arrhenius type equation:

$$y^2 = 6.616 \times 10^{-35} . \left(1.625 - 6.25\, w_{Mo}\right) . \frac{dF}{dt} . e^{-\frac{3196}{T}} . t \qquad (2)$$

where y is the fuel-matrix interaction thickness (m), w_{Mo} is the weight fraction of Mo in the fuel alloy, dF/dt is the fission rate density in the fuel particle (fissions/m^3/s), T is the local meat temperature (K) and t is time (s). The coefficients of correlation (2) were chosen to fit with the measurements on French irradiation experiments. Other models are issued of the PLATE code developed by DOE/ANL. [4]

The evolution of the meat composition (fuel, matrix, fuel particles/Al matrix interaction and porosities) is calculated throughout the irradiation taking into account vanishing of as-fabricated porosities, fuel swelling due to fission products and the thickness of chemical interaction between the fuel particles and the Al-matrix. The fuel particles are modeled in a distribution of particle sizes which can be spherical (for atomized particles) or not. In the latter case, a shape factor is applied. The interaction volume fraction is calculated through this distribution and the interaction thickness.

The meat volume is calculated in each cell of the meat mesh throughout the irradiation by adding fuel, matrix, interaction and porosities volumes. This volume, compared with the initial volume, gives the meat swelling to apply for the mechanical calculation. This loading is applied isotropically.

3. Code validation

MAIA V2.0 has been qualified on analytical test-cases to guarantee the consistency of the code results.
MAIA V2.0 has been validated for U-Mo fuels on the French irradiations (IRIS 1 [5], IRIS 2 [6] and FUTURE [7]) and on some RERTR-3 mini plates [8]. The available PIE measurements (clad oxide layer thickness, fuel-matrix interaction thickness, volume fractions and plate swelling) are in rather good agreement with MAIA results (cf. Figure 4, Figure 5 and Figure 6). For IRIS 1, IRIS 2 and FUTURE, clad aluminum alloy is AG3, irradiation duration was 241, 57.9 and 40 days and the maximum external plate temperature was 68, 93 and 134℃ res pectively.

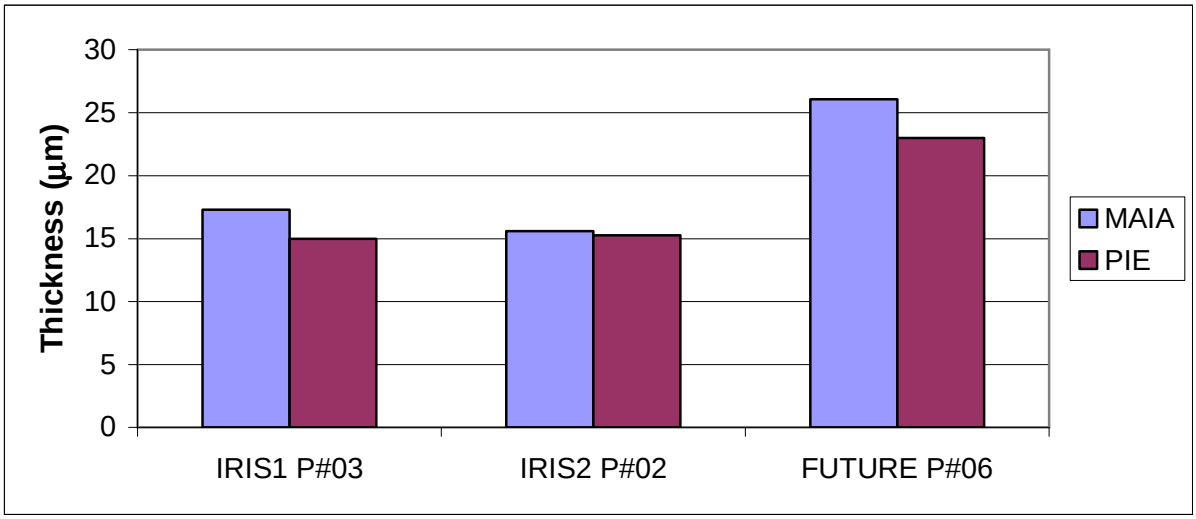

Figure 4: Clad oxide thickness.

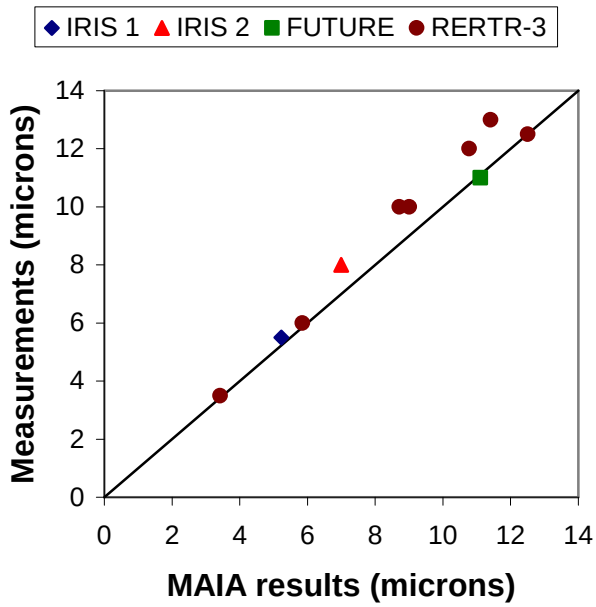

Figure 5: Fuel-matrix interaction thickness

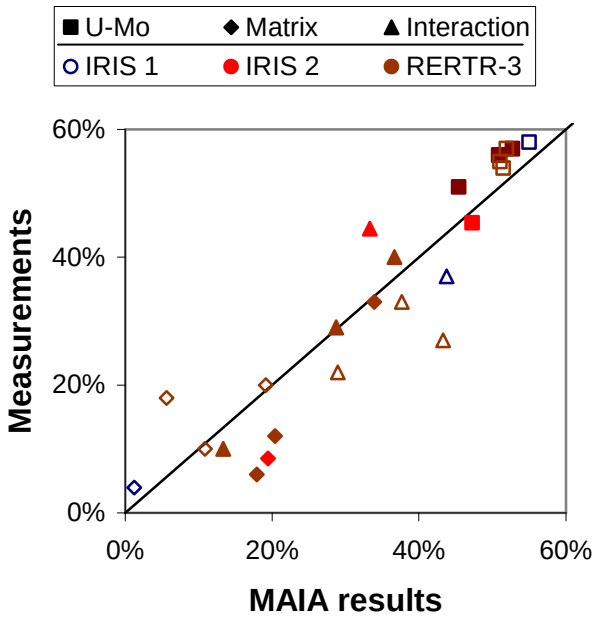

Figure 6: Volume fractions

In Figure 6, the shape of the mark indicates the meat constituent (U-Mo, matrix or interaction) and its color indicates the experiment (IRIS 1, IRIS 2 or RERTR-3). Full marks are for atomized fuels and other for ground fuels.
Fuel volume fractions calculated are in good agreement with PIE as they do not evolve too much during irradiation: the fuel which reacts with the Al matrix is compensated by the fuel swelling. But some disparity is observed on matrix and interaction volume fractions between calculations and measurements. This should be improved in the next version by having a better interaction model (whose trend is to underestimate interaction thickness and thus interaction volume fraction) and by adjusting the shape factor for ground fuels which seems to be overestimated. Parametric studies have also highlighted the sensibility of particles diameter distribution that has to be known accurately. These data are nevertheless not always available.

4. Results on IRIS 2

To illustrate other possible outputs of MAIA, some results obtained on IRIS 2 are presented.
IRIS 2 was irradiated in OSIRIS in 2003. Plates are made with atomized U-Mo fuel. The plate calculated with MAIA (U7MT2002) is the one that reached the highest burnup (39.8 %). Heat flux was rather high: 238 W/cm^2 maximum (cf. Figure 7). Calculation was made in the maximum flux plane.

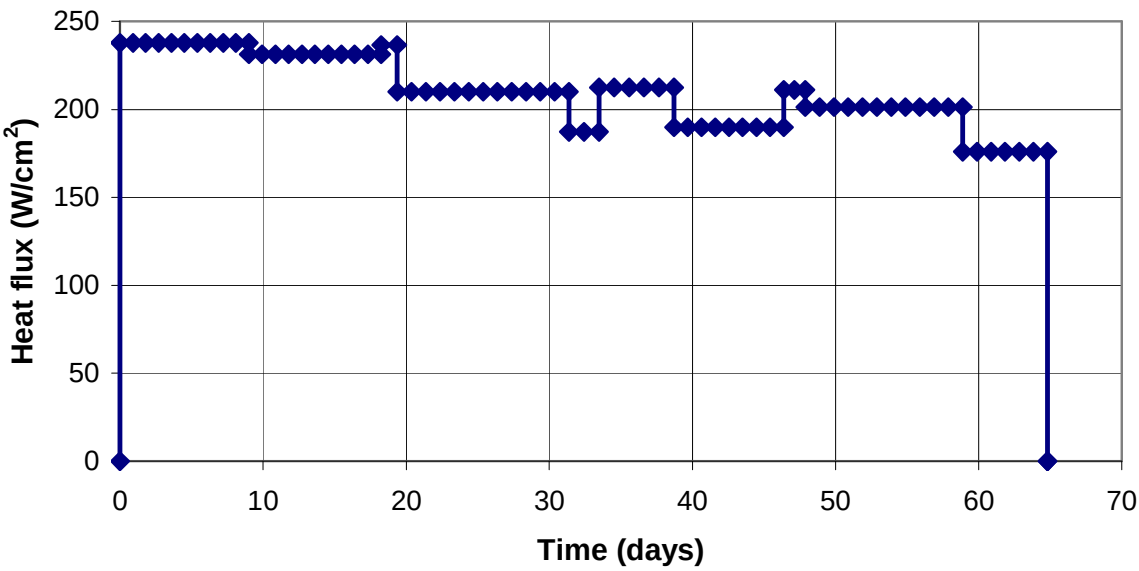

Figure 7: IRIS 2 - Heat flux

Temperatures calculated in IRIS 2 are shown in Figure 8.
At the end of irradiation, the greatest part of thermal gradient is in the cladding oxide layer. The maximum meat temperature is around 110℃ and the external plate temperature is around 80-90℃.

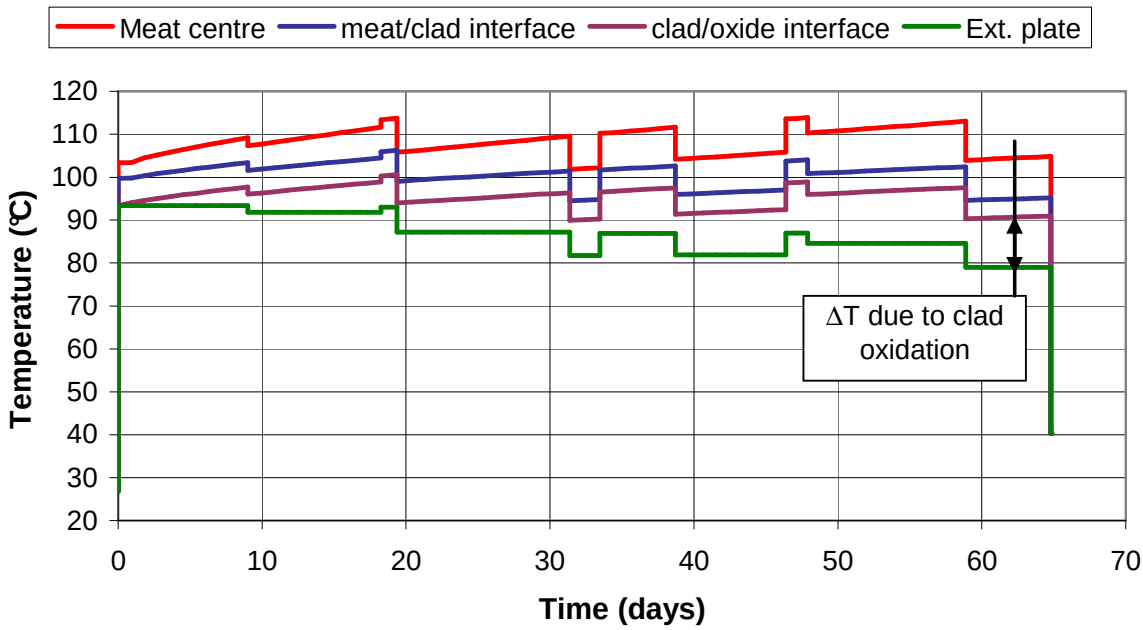

Figure 8 : IRIS 2 - Temperatures in the middle of maximum flux plane

Meat strains in the thickness are much higher than in the width of the plate in spite of an isotropic loading is applied (cf. Figure 9). This is a consequence of the creep of the meat and plate geometry. It is an improvement in modeling since, in previous versions of the code, creep in the meat could not be activated and meat swelling had to be applied only in the thickness of the plate to obtain a plate thickness consistent with the measurements [9].

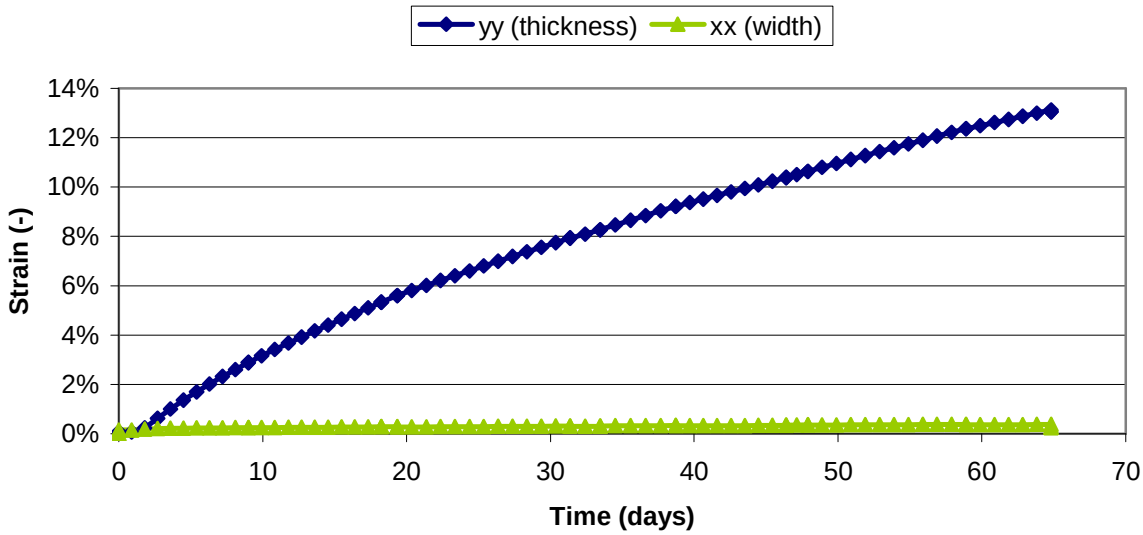

Figure 9: IRIS 2 - Strains in center meat

The induced swelling is consistent with plate thickness measured after each cycle (cf. Figure 10). Pillowing appeared during the last cycle. As this phenomenon is not modeled in MAIA, the calculated plate thickness is only consistent with measurements outside the pillowing zone.

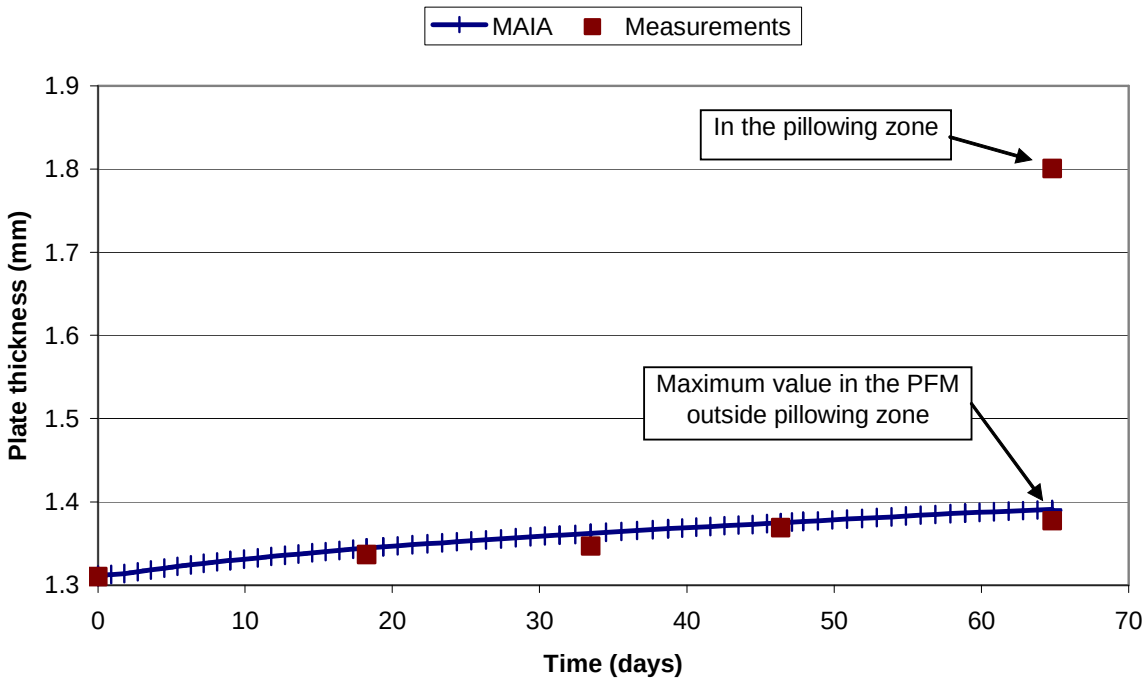

Figure 10: IRIS 2 - Plate thickness in MFP

At the beginning of irradiation, cladding is in compression and meat in tension due to a higher thermal expansion coefficient of the cladding. Then, with meat swelling, stresses are reversed: the meat becomes in compression and the cladding in tension (cf. Figure 11).

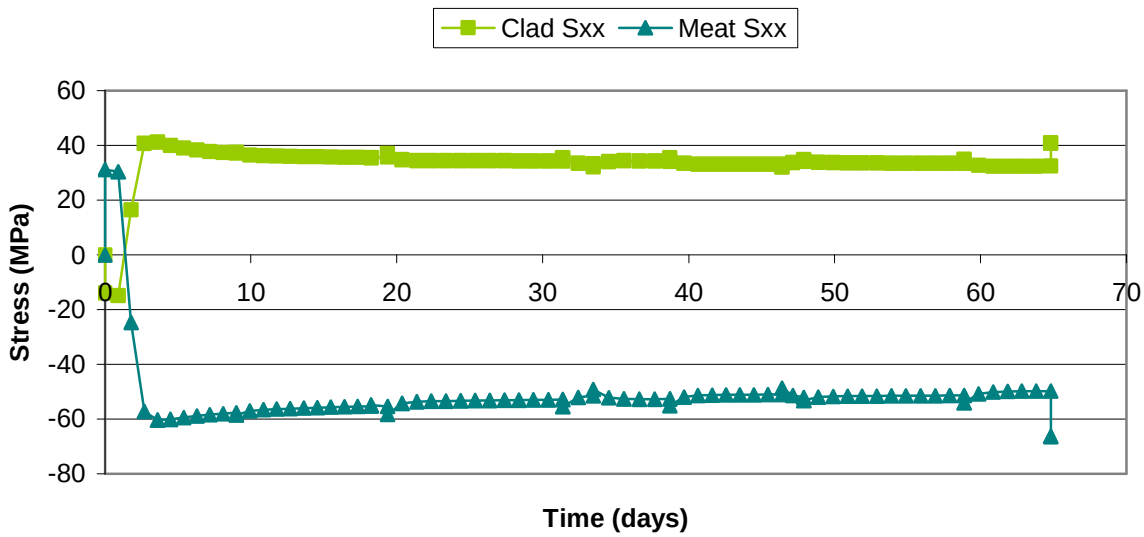

Figure 11: IRIS 2 - Stresses in direction xx (width) in the middle of the plate

5. Conclusion

MAIA V2.0 gives consistent thermal and mechanical results and has been validated on dispersed U-Mo fuels where a good agreement between code results and PIE is observed. MAIA can also be used for U_3Si_2 fuels.
By applying an isotropic meat swelling, mechanical results are now consistent due to creep of the meat.
Some models are still perfectible but MAIA is already a useful tool to understand MTR fuel plates experiments and to support JHR design.
A 3D version is under development to obtain a better accuracy in mechanical results: in 2D, hypotheses must be made on boundary conditions that may not be always valid especially for JHR plates with the crimping of plate's edges. Calculations will have to evaluate differences in displacements and stresses between 2D and 3D modeling.

6. References

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