POST IRRADIATION EXAMINATIONS ON UMO FULL SIZED PLATES - IRIS2 EXPERIMENT -

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ABSTRACT

IRIS2 irradiation was the last irradiation of 4 full sized plates launched by CEA for the French UMo group to test in which operating conditions the coarse porosity forms in the UMo/Al interaction product.
IRIS2 consists in four plates with high uranium loading and U-7wt%Mo atomised powder irradiated up to 60 days at OSIRIS reactor in IRIS device at a peak power of 238 $W.cm^{-2}$. The results show that in the tested conditions pillowing of the plate started from a fission density over 2 10^{21} $fission.cm^{-3}$. Moreover, they show that the fission products and impurities have a key–role in the origin of the excessive plate swelling.

1. Introduction

The French UMo Group program has been launched by 1999 in close collaboration with five partners : CEA, CERCA, COGEMA, FRAMATOME-ANP AND TECHNICATOME[1]. The initial goal of this program was to contribute to the high performances and reprocessable UMo fuel international development (RERTR). To reach this goal the French Group chose to irradiate full-sized experimental plates with low enriched uranium and high uranium loading up to 8 $g.cm^{-3}$.
As a first step of this program, IRIS1 irradiation established the good behaviour of high uranium loading UMo plates, for heat flux up to 140 $W.cm^{-2}$ (~3.4 10^{14} $f.cm^{-3}_{UMo}.s^{-1}$), 67% BU (~4.6 10^{21} $f.cm^{-3}_{UMo}$) with a cladding surface temperature below 75°C[2]. However, as an other step, FUTURE irradiation pointed out fuel performance limitations for higher irradiation flux, i.e. 340 $W.cm^{-2}$ [3](~6.3 10^{14} $f.\ cm^{-3}_{UMo}.s^{-1}$). Indeed this experiment indicated that a porosity can form and coarse in the U-Mo/Al interaction phase. This porosity leads to excessive swelling (pillowing) of the plates. This result was confirmed by others international programs[4].
In order to assess the irradiation limits for which the coarsening porosity forms in the UMo/Al interaction, IRIS2 experiment was initiated in OSIRIS reactor IRIS device. Peak heat flux and cladding wall temperature were 238 $W.cm^{-2}$ and 93°C. The results show that for these operating conditions coarse porosity and pillowing of the plates have also occurred from fission density over $2.10^{21}fission.cm^{-3}_{UMo}$.
The aim of this paper is to present IRIS2 experiment results.

2. IRIS 2 as fabricated plates

For IRIS2 experiment, four experimental plates with high uranium loading (8.3 $g_U.cm^{-3}$) were fabricated by CERCA. The fuel plates consists of U-7wt%Mo atomised fuel powder dispersed in aluminium matrix. The cladding material is AG3-NE.
The main characteristics of the as-fabricated plate meat are summarized in Table 1 : U-7wt%Mo loading is around 51vol% and the porosity lower than 2%.

Plate ref.	Thickness (mm)	U-7wt%Mo (vol%)	Al (vol%)	Porosity (vol%)
P#02	0.51	51.5	47.0	1.5
P#03		51.4	46.9	1.6
P#07		51.6	47.0	1.4
P#08		51.7	47.2	1.1

Table 1 : IRIS2 fuel plates meat main characteristics

3. Irradiation

3.1 Irradiation history

The four plates were irradiated in OSIRIS reactor IRIS irradiation test rig[5]. The IRIS device is associated to an in-pool plate thickness measurements device. It enables to assess plate thickness profiles at each reactor cycle stop.
Peak irradiation heat flux and cladding temperature of the four plates are given Table 2.

		Heat flux ($W.cm^{-2}$)				Cladding surface temperature (°C)			
Cycle n°	**FPD✍**	**P #02**	**P#03**	**P#08**	**P#07**	**P #02**	**P#03**	**P#08**	**P#07**
1	**15.1**	238	217	214	231	93	89	89	92
2	**13.2**	237	216	213	229	93	89	88	91
3	**12.0**	213	201	/	225	88	87	/	91
4	**17.6**	212	206	/	/	88	87	/	/

Table 2 : Maximum Flux Plane (MFP) peak irradiation conditions(✍Full Power Day)

The plate P#08 was removed after the second cycle, due to a slight warping of it during intercycle handling. The irradiation of the three other plates was further stop before reaching the 50% target burnup. Indeed, for safety reason the swelling admissible limit for the plate is 250 µm and this limit was reached at the end of the third cycle for P#07 and at the fourth cycle for the 2 other plates (P#02 and P#03):

3.2 In-pool plate thickness measurements

IRIS 2 plate thickness swelling is given Figure 1 as a function of the fission density. As a comparison IRIS 1[2] and FUTURE[3] experiments swelling are also plotted.
The results show that for IRIS2 irradiation conditions, plate pillowing occurs from around 2 10^{21} $fission.cm^{-3}_{UMo}$. These results are consistent with FUTURE experiment one. For lower irradiation conditions and grounded particles (IRIS1 experiment), no pillowing was observed up to 4.8 10^{21} $fission.cm^{-3}_{UMo}$.

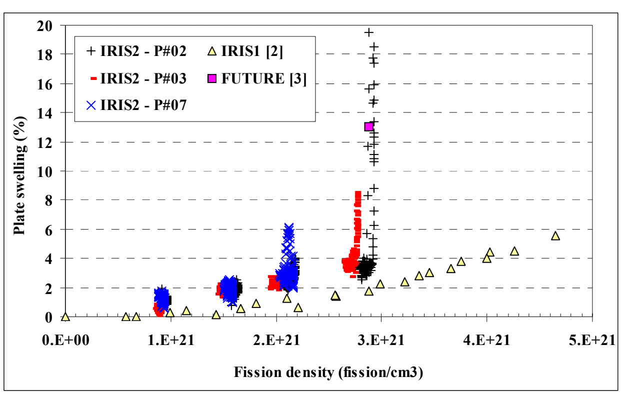


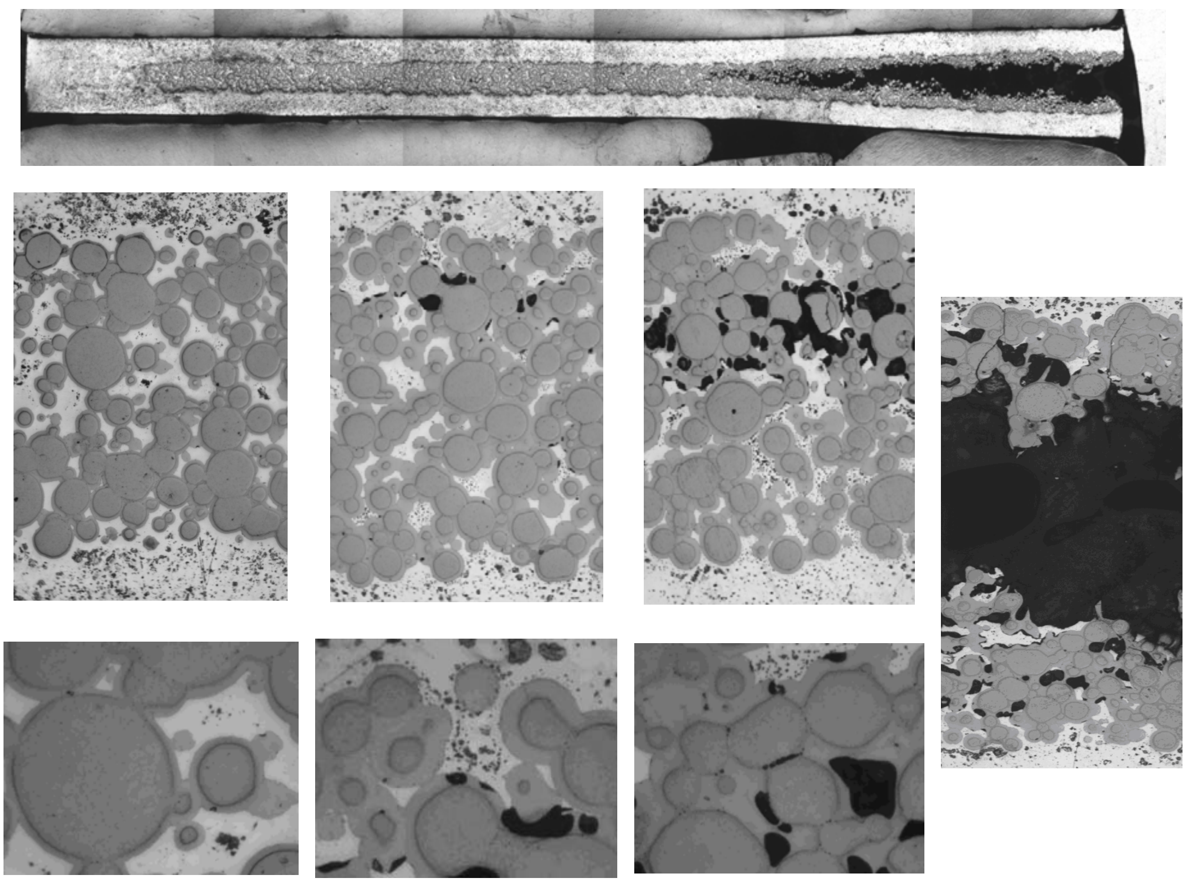
Figure 1 : Plate swelling versus fission density ($fission.cm^{-3}_{UMo}$).

4. Post-Irradiation Examinations (PIE)

A large set of PIE was performed on the most deformed plate, i.e. P#02 at the maximum flux plane. The sample is chosen in order to have the edge of the plate meat together with the large pillowing area. Burnup at this location evolves from 2.8 10^{21} to 2.9 10^{21} fission.cm^{-3}_{UMo} and at the peak temperature in the meat is 112°C[6].

4.1 Metallographic examinations

Metallographs of the sample, shown *Figure 2*, indicate a microstructure similar to FUTURE [3] experiment one. They confirm that the origin of the plate pillowing is coarse porosity at the (U-Mo)-Al interaction product interface with aluminium. All the stages of the porosity formation and coarsening are seen, from no porosity area (*Figure 2*a) to a big hole at the plate pillowing location (*Figure 2*d).
In the pillowing area, it can be seen indications of interaction product plastic deformation but no signs of U-7wt%Mo alloy microstructure evolution.



a) b) c) d)

Figure 2 : Metallographic examinations on IRIS2 Plate P#02 at MFP

4.2 EPMA

X-ray mappings at the different locations identified in *Figure 2* are presented Figure 4. The mappings underline :

- A depletion of molybdenum content observed at the U-Mo alloy grain boundaries. It has already been observed in past experiment with atomised powders[7],
- A fission product accumulation at the interface between interaction product and aluminium matrix. However, for solid fission product, as for example Zr, no evolution of their concentration is visible, while at contrary for Xe, this accumulation disappears as the porosity increases, i.e. from location -a to - d of Figure 4.

Quantitative analyses were also done. They indicate that the aluminium content of the interaction layer decreases continuously from "U-MoAl$_6$" to "U-MoAl$_{4.5}$", respectively from edge of the meat (Figure 4-a) to the pillowing area (Figure 4-d).

4.3 SEM examinations

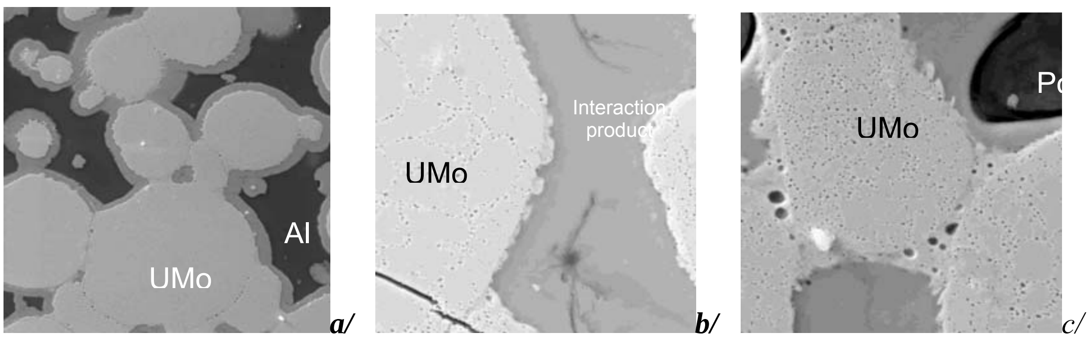


Figure 3 : SEM images of Plate P#02 meat.

SEM examinations presented Figure 3 show :

- fission gas bubble precipitation at the grain boundaries of UMo alloy particles, where the Mo content is lower (-b & -c),
- no fission gas bubbles are observed in the "U-MoAl" interaction layer (-a, -b & -c),
- when 2 UMo particles are close together, some link, like sintering link are observed in between the particles, larger fission gas bubbles are observed in the linking compound (-c).
- the UMo particles interface with UMoAl interaction product is not smooth, it could indicate that interaction occurs at preferential location, as grain boundaries (-b & -c),
- dark lines are visible at the interfaces where two interaction layer meet together (-b).

5. Discussion

The results obtained indicate that, during irradiation, as the temperature increases, the aluminium content in interaction compound decreases from "(U-Mo)Al$_6$" at the coldest to "(U-Mo)Al$_{4.5}$" at hottest position of IRIS2 sample.
These results are consistent with previous experiments. Indeed, for IRIS 1[2] low temperature experiment, "(U-Mo)Al$_7$" compound has been found while for higher temperature experiment[3] (FUTURE) it was (U-Mo)Al$_{3\text{-}4}$".
The origin of the large pores development in the interaction product is still not clear, but from the results it seems that the fission products have a key-role in it. Indeed, it seems that while the interaction layer grows, the fission products (FP) and impurities (of aluminium matrix) are "pushed" at its periphery (see dark interaction borders Figure 3-b). One explanation of that could be a low solubilization of the FP in the interaction product. Then the reaction is stopped at some weak location, at the interaction product / aluminium interface when the amount of FP and impurities is high enough. It could be the porosity formation beginning. Moreover, when porosity started to form, gases could progressively fill it by diffusion process. This phenomenon is enhanced by the local temperature

increase due to the low conductivity of the so-formed porosity. This process is irreversible and spiral out of control and leads to porosity coarsening.
On the other hand, IRIS2 experiment indicates a good behaviour with temperature of the U-7wt% Mo alloy itself. Indeed, even at rather high temperature (pillowing area) no indications of excessive FG release or bubble growth are observed in the fuel particles.

6. References

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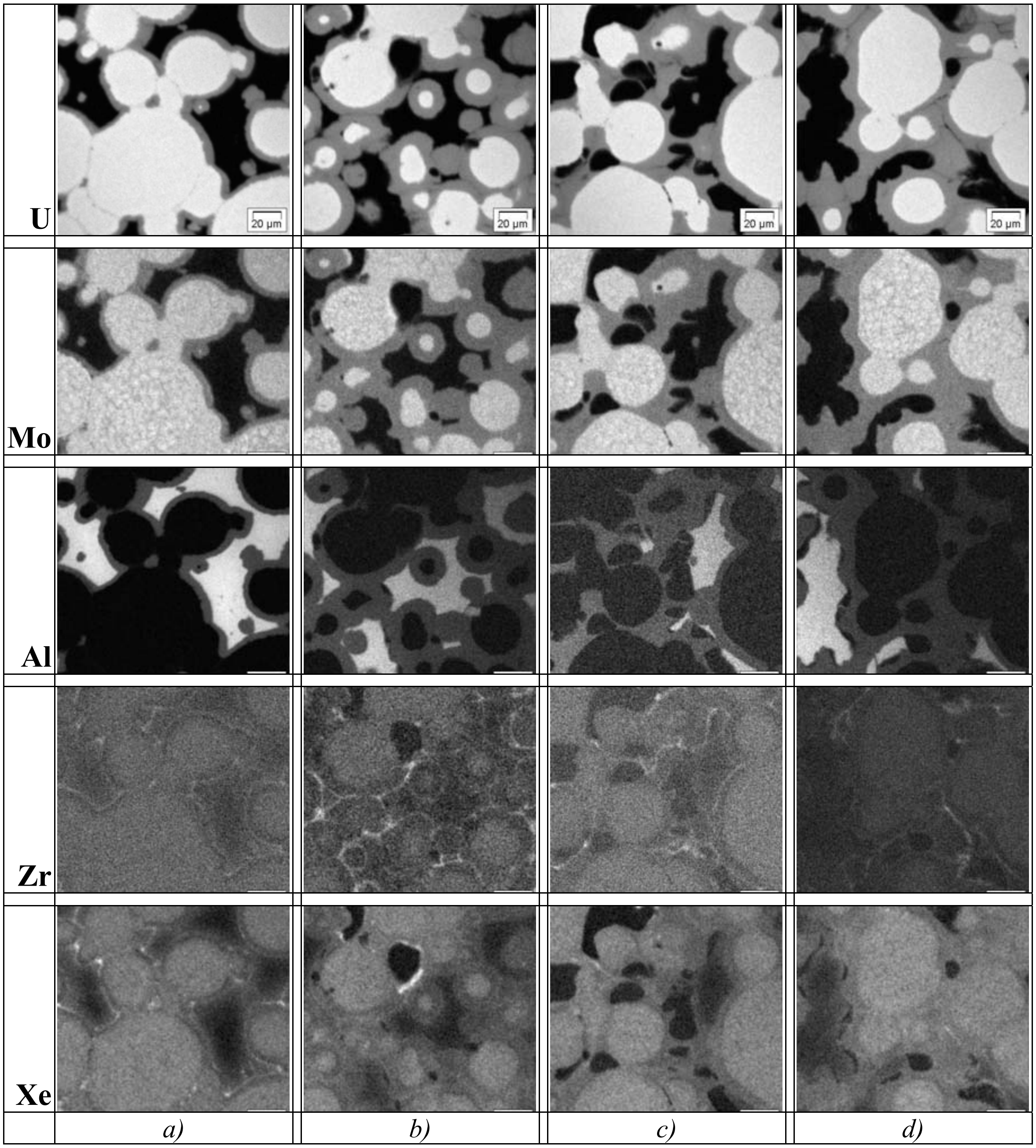

Figure 4: X-ray mappings of IRIS2 plate P#2 at several locations.