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UPDATE OF FUEL MEAT SWELLING DETERMINATION OF COATED-(U-7Mo)/Al DISPERSION FUEL FROM EMPIrE

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Introduction

EMPIrE

The EMPIrE experiment was designed to investigate the influence of various parameters on the performance of the coated U-Mo/Al dispersion fuel systems. It included 44 dispersion fuel plates, with six fabrication parameters (coating type, coating technique, fuel particle size distribution, fuel powder source, Mo content in fuel, heat treatment) and one operational variable (fission rate).

- Previously, a study of overall performance of EMPIrE plates and separate effects of several variables on fuel swelling based on NDE data [1] and an initial assessment of fuel meat swelling using nominal fuel meat thickness [2] were published.

Objectives of the present study

To continue the EMPIrE data analysis focusing on the determination of fuel meat swelling, given the uncertainties related to the as-fabricated porosity determination in coated U-Mo/Al plates.

- Various methods were explored to improve the determination of fuel meat swelling.

[1] W.A. Hanson et al., "Non-destructive analysis of swelling in the EMPIrE fuel test," J. Nucl. Mater. 564 (2022) 153683.

[2] L.M. Jamison et al., "EMPIrE fuel meat swelling analysis," RRFM, 2022.

Fuel meat swelling determination

$$\left(\frac{\Delta V}{V_0}\right)_m = \frac{t_p - t_{p,0} - t_{ox}}{t_{m,0}} \simeq \frac{t_p - t_{p,0}}{t_{m,0}} \qquad \text{(Eq. 1)}$$

t_p = post−irradiation plate thickness

$t_{p,0}$ = pre−irradiation plate thickness

t_{ox} = cladding oxide film thickness by eddy-current test

$t_{m,0}$ = pre-irradiation meat thickness

Pre-irradiation meat thickness cannot be directly measured prior to irradiation.

→ Typically, the nominal value is used assuming the plate is built accurately by the specification (initial evaluation strategy).

→ This study investigates different methodologies for determining fuel meat thickness, both pre- and post- irradiation, in order to improve fuel meat swelling evaluation that will be used to evaluate test variables.

➔ Other techniques, such as X-ray radiography and UT scan, can be explored to provide further information related to fuel/fuel meat thickness [1].

Fuel meat swelling determination methods

- Method 1
  - Plate thickness before and after irradiation measured by profilometry
  - Nominal pre-irradiation fuel meat thickness
- Method 2
  - Plate thickness before and after irradiation measured by profilometry
  - Pre-irradiation fuel meat thickness measured using OM of irradiated plates
- Method 3
  - Plate thickness before and after irradiation measured using OM of irradiated plates
  - Pre-irradiation fuel meat thickness measured using OM of irradiated plates

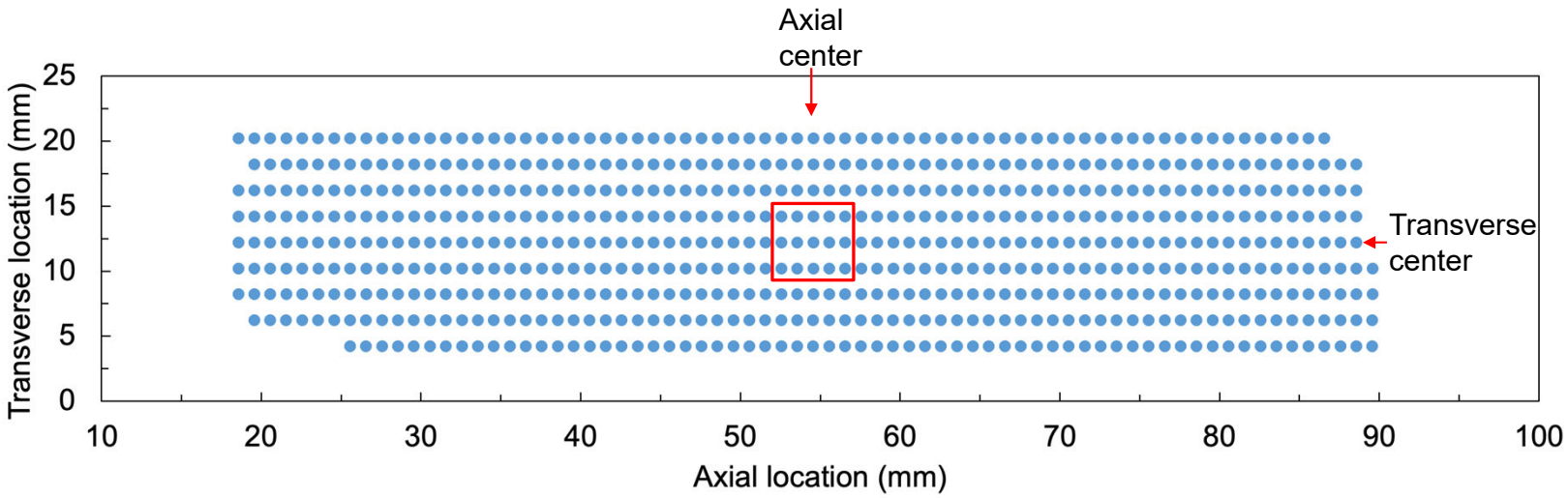
Fuel meat swelling determination: Method 1

$$\left(\frac{\Delta V}{V_0}\right)_m = \frac{t_p - t_{p,0}}{t_{m,0}} \quad \text{(Eq. 2)}$$

t_p, $t_{p,0}$ = *profilometry data*
$t_{m,0}$ = *nominal pre-irradiation meat thickness*

Fuel meat swelling analysis focusing on fuel meat center region

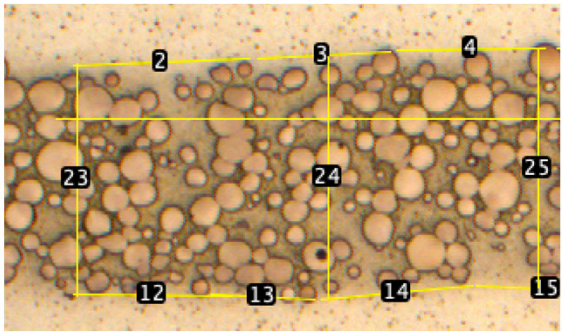
- To avoid creep and to be consistent with other methods based on coarser plate thickness measurements
- 4 mm (axial) x 4 mm (width) → 15 plate thickness data → average



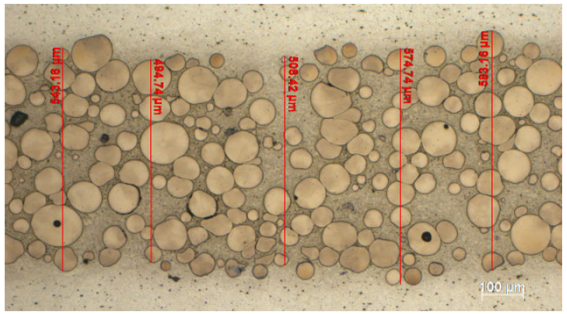
Blue dots indicate plate thickness data points by profilometry (pre- and post-irradiation).

Is the nominal pre-irradiation meat thickness accurate?

Comparison to pre-irradiation meat thickness measured from OM images of archive plates



Guide-line method (Argonne)



Particle-to-particle method (INL)

OM of the archive plate EMPI0516 (ZrN-coated U-7Mo/Al)

Two independent fuel meat thickness measurements

- Guide-line method (Argonne)
- Particle-to-particle method (INL)

Comparison of fresh fuel meat thickness measurements

	Guidelines (Argonne)	Partile-to-Particle (INL)
Plate ID	**Fresh fuel meat thickness (mm)**	**Fresh fuel meat thickness (mm)**
115	0.587	
516	0.587	0.560
703	0.614	0.585
715	0.628	
811	0.611	
817	0.623	0.615
2203	0.557	0.552
Average	0.601	0.578

Nominal value 0.508 mm

Measured pre-irradiation fuel meat thicknesses from both methods are considerably larger than the nominal value.

→ If the nominal meat thickness is used, fuel meat swelling will be over-estimated.

Fuel meat swelling determination: Method 2

$$\left(\frac{\Delta V}{V_0}\right)_m = \frac{t_p - t_{p,0}}{t^*_{m,0}} \qquad \text{(Eq. 3)}$$

t_p = post-irradiation plate thickness from profilometry
$t_{p,0}$ = pre−irradiation plate thickness from profilometry
$t^*_{m,0}$ = pre-irradiation fuel meat thickness from profilometry and OM image

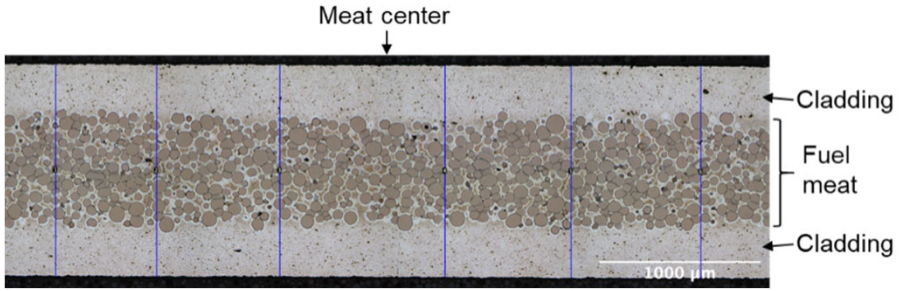
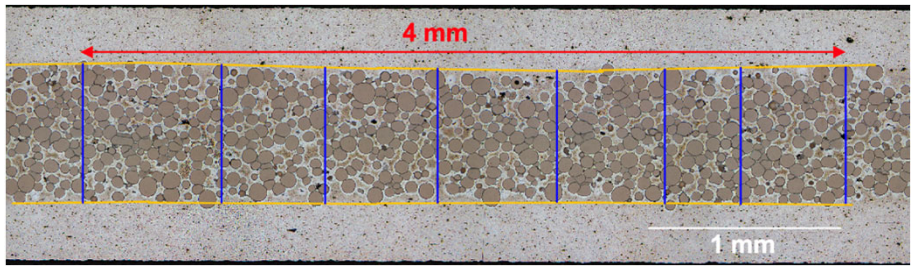


Plate thickness measurement from irradiated EMPI0818



Meat thickness measurement from irradiated EMPI0818

$$t^*_{c,0} = \frac{t^*_p - t^*_m}{2}$$

t^*_p = plate thickness from OM, t^*_m = meat thickness from OM

$t^*_{c,0}$ = cladding thickness from post-irradiation OM

- Cladding thickness remains invariant during irradiation.
- So, by subtracting the meat thickness from plate thickness, cladding thickness can be found.

$$t^*_{m,0} = t_{p,0} - 2\,t^*_{c,0}$$

- By subtracting the cladding thickness from the pre-irradiation plate thickness, pre-irradiation meat thickness can be found.

Fuel meat swelling determination: Method 3

→ Use OM for plate thickness (pre- and post- irradiation) and pre-irradiation meat thickness.

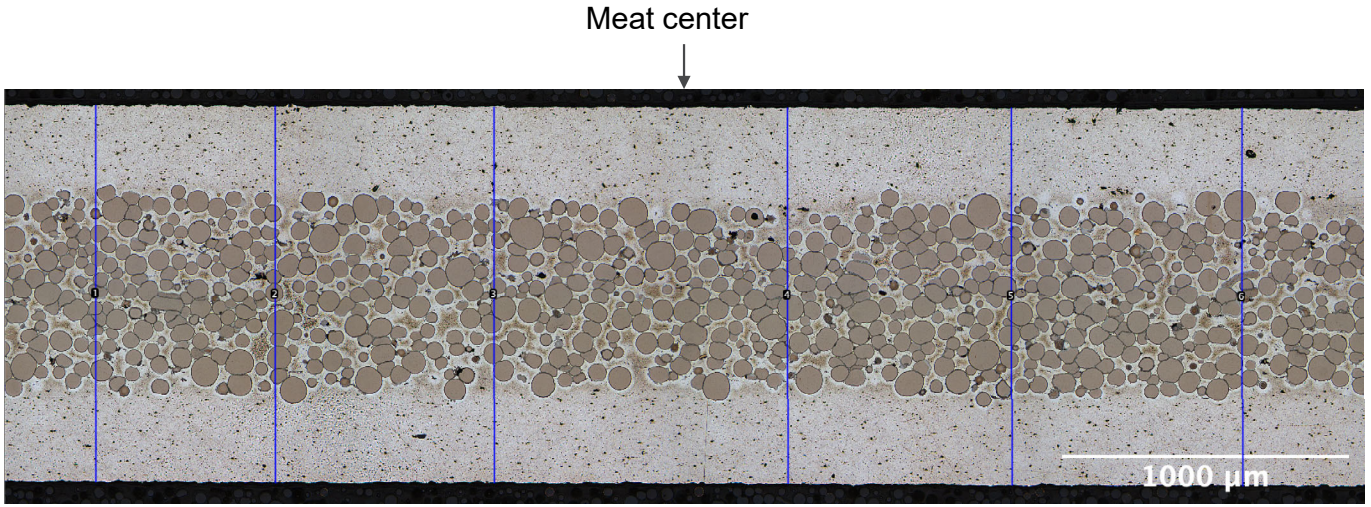
$$\left(\frac{\Delta V}{V_0}\right)_m = \frac{t_p^* - t_{p,0}^*}{t_{m,0}^*} \qquad \text{(Eq. 4)}$$

t_p^* = post−irradiation plate thickness measured using OM

$t_{p,0}^*$ = pre−irradiation plate thickness measured using OM

$t_{m,0}^*$ = pre−irradiation meat thickness measured using OM

t_p^* = post−irradiation plate thickness measured using OM



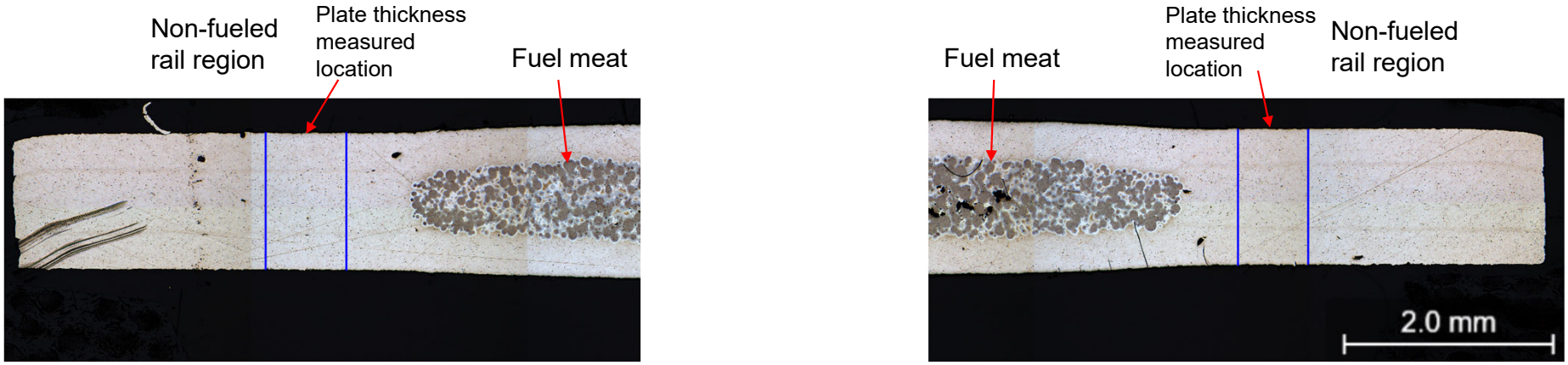
OM image of irradiated EMPI0818

$t^*_{p,0}$ = pre−irradiation plate thickness measured using OM

Because cladding thickness remains unchanged by irradiation,
→ post-irradiation plate thickness in the rail regions remains unchanged from the pre-irradiation thickness.

$$t^*_{p,0} \simeq t_{p,r}$$

$t_{p,r}$ = plate thickness measured in rail region of irradiated plates



OM images of the meat end regions of irradiated EMPI0109

Comparison of pre-irradiation plate thickness between profilometry and OM measurement

U-7Mo Plates

Plate ID	Method 1 Fuel-loaded region profilometry ($t_{p,0}$)	Method 3 Rail region OM ($t^*_{p,0}$)
EMPI0109	1.289	1.285
EMPI0117	1.280	1.281
EMPI0512	1.276	1.273
EMPI0518	1.275	1.279
EMPI0702	1.294	1.288
EMPI0706	1.280	1.273
EMPI0712	1.286	1.290
EMPI0813	1.264	1.269
EMPI0818	1.286	1.280
EMPI0820	1.257	1.260
EMPI0821	1.267	1.271
EMPI0905	1.260	1.266
EMPJ2207	1.274	1.293
Average	1.276	1.278

U-10Mo Plates

Plate ID	Method 1 Profilometry ($t_{p,0}$)	Method 3 Rail region OM ($t^*_{p,0}$)
EMPI2003	1.288	1.294
EMPI2007	1.275	1.293
Average	1.282	1.294

Pre-irradiation plate thickness measured in the rail regions is consistent with the pre-irradiation plate thickness at the meat center region by profilometry.

Pre-irradiation meat thickness for Method 3

$$t^*_{m,0} = t^*_{p,0} - 2\,t^*_{c,0}$$

$t^*_{m,0}$ = pre-irradiation meat thickness
$t^*_{c,0}$ = pre-irradiation cladding thickness (the same data from Method 2)

Therefore, measurement of plate thickness by OM in the rail region can be used to determine pre-irradiation plate thickness.

Comparison of measured pre-irradiation meat thickness from Method 2 and Method 3 with nominal value

Measured pre-irradiation meat thickness, U-7Mo (mm)

Plate ID	Method 2	Method 3
EMPI0109	0.609	0.605
EMPI0117	0.592	0.593
EMPI0512	0.597	0.594
EMPI0518	0.626	0.630
EMPI0702	0.626	0.620
EMPI0706	0.674	0.667
EMPI0712	0.653	0.656
EMPI0813	0.641	0.646
EMPI0818	0.656	0.650
EMPI0820	0.632	0.635
EMPI0821	0.648	0.652
EMPI0905	0.638	0.644
EMPI2207	0.550	0.570
Average	0.626	0.628

U-7Mo nominal pre-irrad. meat thickness = 0.508 mm

Measured pre-irradiation meat thickness, U-10Mo (mm)

Plate ID	Method 2	Method 3
EMPI2003	0.655	0.661
EMPI2007	0.584	0.601
Average	0.620	0.631

U-10Mo nominal pre-irrad. meat thickness = 0.533 mm

Meat thickness of U-7Mo/Al archive plates

Plate ID	Archive plate meat thickness (mm)
115	0.587
516	0.587
703	0.614
715	0.628
811	0.611
817	0.623
2203	0.557
Average	0.601

- The average of the measured pre-irrad. meat thickness of the U-7Mo plates deviates from the nominal pre-irrad. meat thickness by 23% (for Method 2) and 24% (for Method 3).
- Consistent with the measured results on archive plates

Comparison of meat swelling (%) between three methods

Plate ID	Fission density center-average (10^{21} f/cm^3)	Method 1	Method 2	Method 3
EMPI0117	4.16	22.1	19.0 ±1.4	16.3 ±1.6
EMPI0109	5.84	32.5	27.1 ±1.4	25.0 ±2.2
EMPI0518	3.05	10.8	8.8 ±0.7	8.8 ±0.9
EMPI0512	5.79	29.2	24.9 ±2.2	23.4 ±2.3
EMPI0712	2.97	5.4	4.2 ±0.5	5.4 ±0.7
EMPI0706	4.64	11.5	8.7 ±0.5	12.4 ±0.9
EMPI0702	5.69	18.6	15.1 ±1.1	17.1 ±1.0
EMPI0813	2.69	5.0	4.0 ±0.4	1.7 ±0.5
EMPI0818	3.29	3.6	2.8 ±0.3	5.1 ±0.7
EMPI0820	5.10	10.0	8.1 ±0.7	7.1 ±0.7
EMPI0821	6.24	15.8	12.4 ±0.5	12.8 ±0.9
EMPI0905	6.06	20.3	16.2 ±1.0	14.8 ±2.0
EMPI2003	2.74	4.7	3.9 ±0.4	1.4 ±0.7
EMPI2007	5.05	22.0	20.0 ±1.1	15.8 ±1.8
EMPJ2207	5.13	19.1	17.6 ±0.7	13.4 ±1.4

→ Method 1 has sound basis if the nominal pre-irradiation meat thickness is accurate.

→ Method 2 is reliable, because it captures more pre-irradiation microstructural information than Method 1. Applicable to plates even without OM images if the average measured value is used.

→ Method 3 is consistent with Method 2, providing confirmatory information for Method 2, and non-reliant on data from other measurement method (such as profilometry).

SUMMARY

- The post-irradiation examination data of the EMPIrE irradiation campaign were analyzed focusing on U-7Mo/Al dispersion fuel meat swelling.
- Three methods were used to determine meat swelling.
  - the first method is the standard method that uses plate thickness change measured by profilometry and nominal pre-irradiation fuel meat thickness.
  - the second method uses plate thickness change measured by profilometry and pre-irradiation fuel meat thickness estimated on OM images. This method appears to be reliable.
  - the third method uses OM images to measure plate thickness change and to estimate pre-irradiation meat thickness.
- The updated meat swelling data will be used to:
  - Re-examine the impact of various test variables on coated U-Mo/Al swelling behavior.
  - Assess the suitability of using the EMPIrE data, combined with other test data, to develop fuel meat and fuel phase swelling correlations of coated U-7Mo/Al fuels.
- **Continued analysis of the EMPIrE data will support the development and qualification of this fuel system for use in reactor conversion from HEU to LEU.**

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