BENCHMARK BETWEEN THE PLEIADES/MAIA AND DART FUEL PERFORMANCE CODES ON THE E-FUTURE U-Mo/Al DISPERSION FUEL TEST

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DE LA RECHERCHE À L'INDUSTRIE

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Context

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CONTEXT

Context

- Collaboration between ANL (Argonne National Laboratory) and CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives)
- Studies : benchmarking of MTR fuel simulation codes DART (ANL) and MAIA (CEA)
- Objective : to improve reliability and predictability of codes

Previous benchmark effort [RRFM2019]

- 2D calculations
- Studies : influence of code structure on calculated temperatures – Separate effect tests
- Results : relatively close; differences amplified when models include a feedback loop with temperature

Scope of the current benchmark

- DART-2D vs MAIA 3D
- Phase-I : code to code comparison → all parameters compared
- Phase-II : comparison with non-destructive and destructive characterization results [JNM430] [JNM441]

[RRFM2019] S. Valance, A. Monnier, H. Palancher (CEA) B. Ye, A. Yacout (ANL), RRFM, 2019
[JNM430] S. van den Berghe & al., Journal of Nuclear Materials: 430, pp. 246-258, 2012
[JNM441] Ann Leenaers &. al., Journal of Nuclear Materials: 441, pp. 439-448, 2013

Computational codes description

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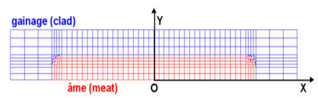
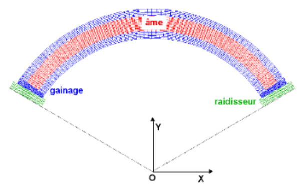
PLEIADES/MAIA

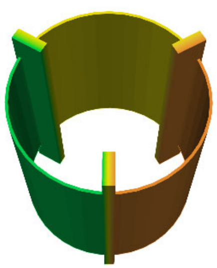
FUEL PLEIADES SIMULATION

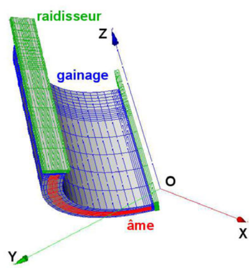
- PLEIADES multiphysics and multiscale fuel element simulation platform (PWR ALCYONE - SFR GERMINAL - MTR MAIA - …)

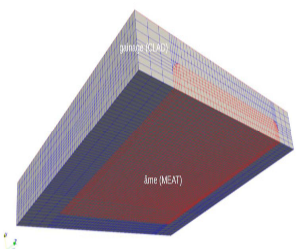
- MTR multi dimensions plates:
  - ❑ 2D or 3D
  - ❑ Plate or curved
  - ❑ One plate or one ring (=3 curved plates)











- Multiphysics code for U_3Si_2 and U-Mo fuel
  - ❑ Thermal and mechanical code
  - ❑ Specific model for material evolution under irradiation (oxide layer, swelling, …)
  - ❑ Thermohydraulic model

- Optimized (C++) and distributed version control (GIT) code

DART (Dispersion Analysis Research Tool)

- An integrated fuel performance code developed at Argonne for simulating irradiation behaviors of research and test reactor fuels.

- Three calculation branches for different fuel types: U-Mo/Al dispersion fuel, U-Mo monolithic fuel, and U_3Si_2-Al dispersion fuel.
  - ❑ Mechanistic and empirical fuel swelling model
  - ❑ 1D and 3D (on going) heat transfer model
  - ❑ Fuel thermal conductivity degradation model

- The code simulates both miniature-sized and full-size plates.

- The output information includes the evolution of:
  - ❑ Fuel meat swelling
  - ❑ Fuel meat microstructure
  - ❑ Fuel meat temperature
  - ❑ Fission gas bubble morphology
  - ❑ Local fuel plate deformation due to swelling

Phase-I full code to code comparison

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MODELS AND PARAMETERS DEFINED FOR THE COMPARISON

	MAIA	DART
IL composition *	$(U,Mo)Al_4$	
Initial fuel particles volume fract	48%	
Fuel swelling due to fission products swelling and gazeous swelling	correlation of RERTR-2007 "MTR Plates modeling with MAIA"	correlation of JNM 419 (2011) 291-301
	Analytic comparison : relatively similar results	
UMo conductivity (as a function of irradiation)	Method presented in [RRFM2004]	Bruggeman model [ANL09-31]
Hydraulic diameter	12 mm	
Fluid velocity	10 m/s	
External pressure	1.2 MPa (nominal BR2 coolant pressure)	
Boundary conditions	DART : thermal hydraulics calculation, MAIA : DART results imposed	
Parameters analysed	Temperatures, IL thickness, oxide thickness, volume fractions,	

*This composition was chosen as the density of UAl_4 is available. Parametric study were performed for the IL composition of $(U,Mo)Al_3$ – $(U,Mo)Al_6$. Its impact on meat constituent volume fractions is small, and some effect on meat swelling was observed.

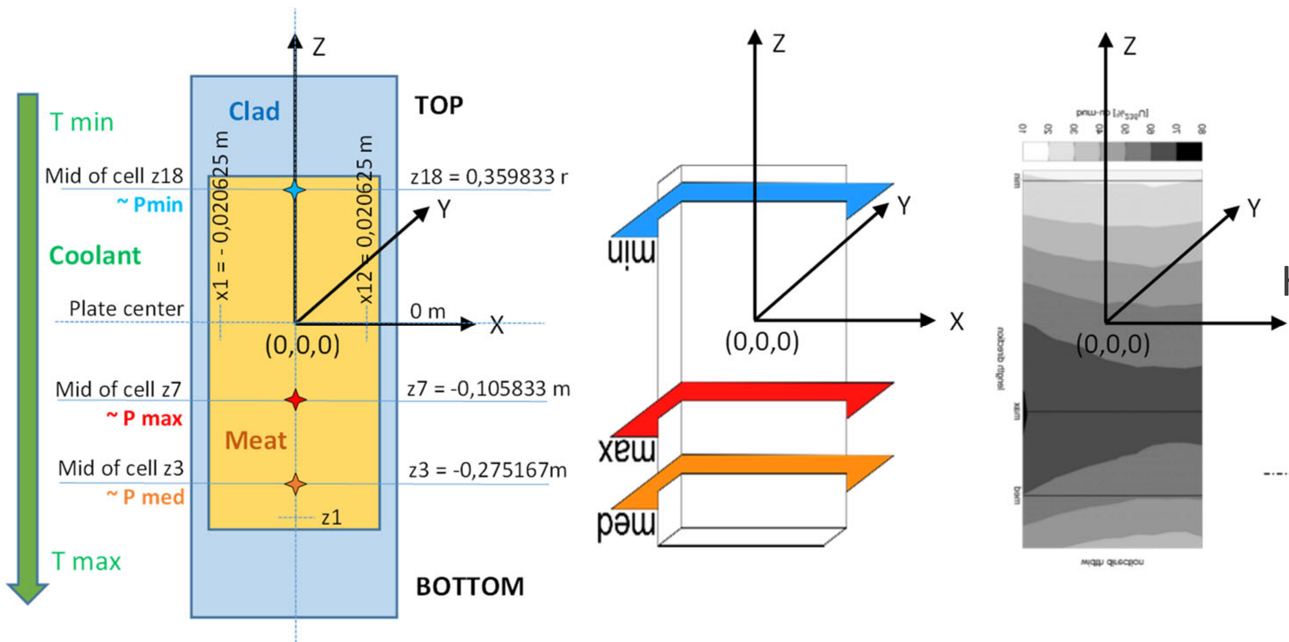
CASES DESIGNED FOR THE CODE-TO-CODE COMPARISON

	% Si	(U,Mo)Al conductivity (W/m·K)	pH	oxidation model	Fuel swelling correlation	
					CEA	ANL
UMo Phase-I	0%	5	6.0	Model 1 [ANL18-10]	[RERTR2007]	[JNM419]
	0%	10	6.0			
	4%	5	6.2			
	4%	5	6.0			
UMo Phase-II	4%	5	6.2	Model 2 [JNM529]		

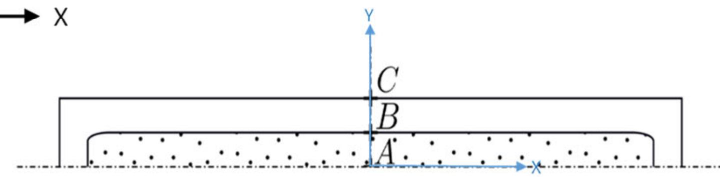
[ANL18-10] ANL-18/10 - Hee Taek Chae & al. - September 2018
[RERTR2007] RERTR-2007 - V. Marelle, S. Dubois, M. Ripert, J. Noirot, P. Lemoine (CEA)
[JNM529] Kim & al. J. Nucl. Mater. 529 (2020) 151926
[JNM419] Kim and Hofman, J. Nucl. Mater. 419 (2011) 291-301.

PLATE GEOMETRY AND LOCATION SELECTED FOR COMPARISON

- The full plate of E-FUTURE 4202 was simulated by both codes.
  - The results were compared at the fuel meat center at three axial locations, selected to represent the minimum, median, and maximum fission density areas of the plate, respectively.



Half plane of fuel meat cross section



A – fuel meat center
B – the center point at the cladding/meat interface
C – the center point at the cladding surface

End-of-life fission density (f/cm^3):

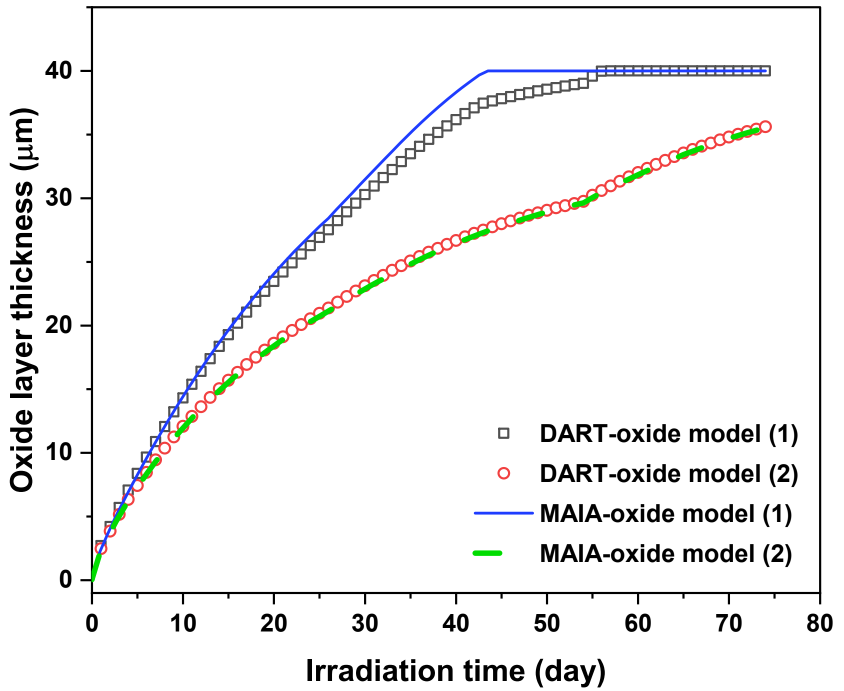
Max	4.64×10^{21}
Med	3.67×10^{21}
Min	1.28×10^{21}

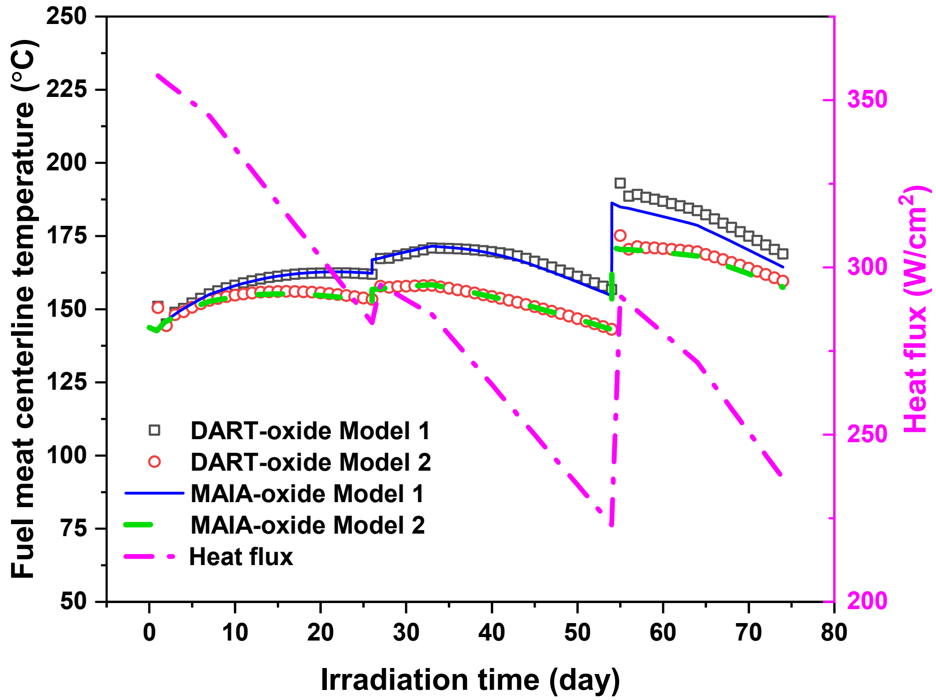
IMPACT OF OXIDE GROWTH MODEL

- Model 2 was updated based on Model 1 to improve its agreement with measured data for high temperature cases.
- Oxide growth Model 2 predicts lower oxide growth than Model 1.
  - Thinner oxide layer → lower fuel meat temperature
- Both codes agree with each other generally.
  - The difference is minimum when Model 2 is used.

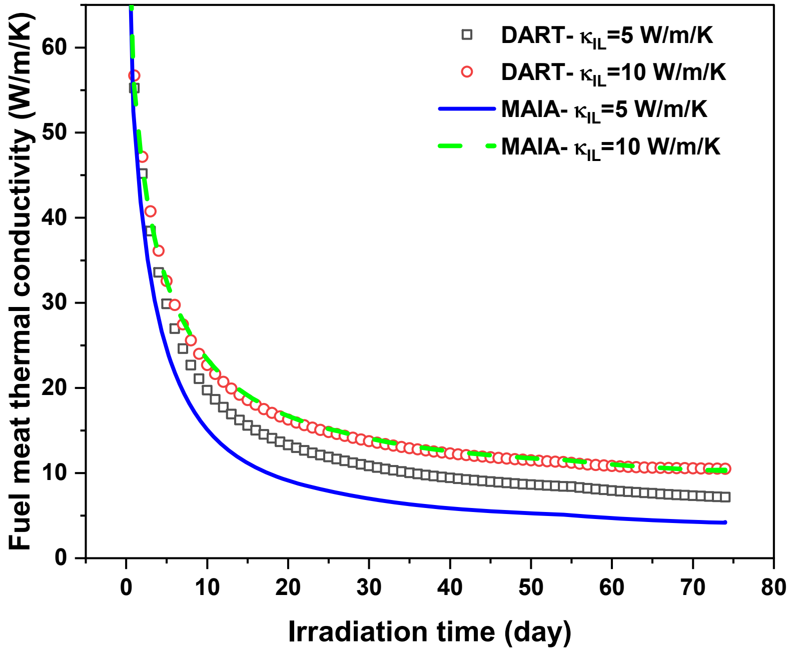
% Si	(U,Mo)Al conductivity	pH	oxidation model
4%	5 W/m·K	6.2	Model 1
4%	5 W/m·K	6.2	Model 2

Calculation results were compared at the max fission density location.



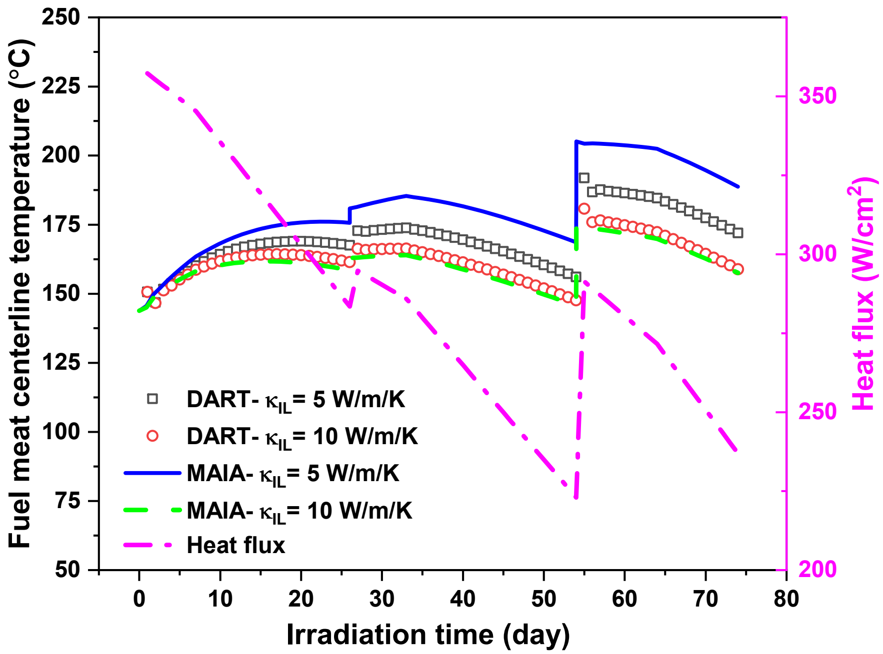


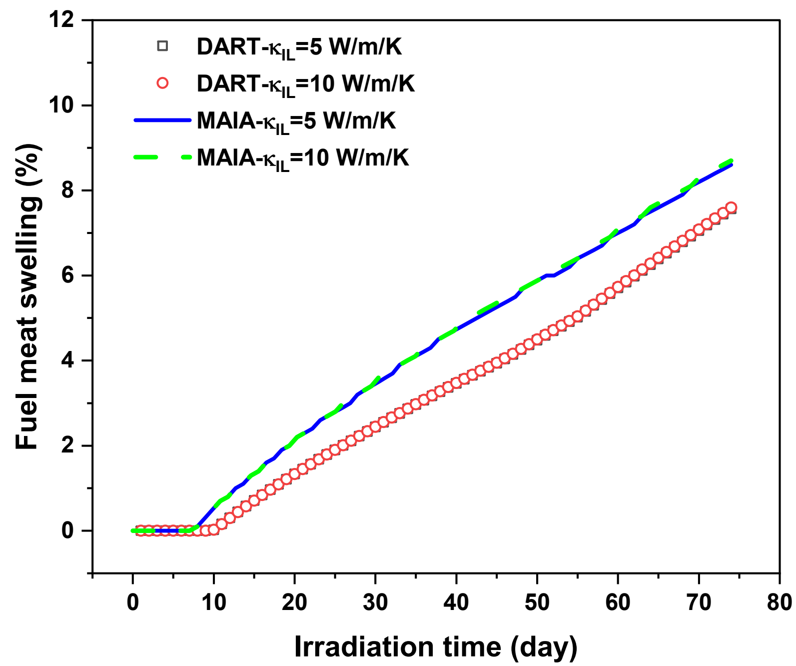
IMPACT OF IL THERMAL CONDUCTIVITY



% Si	(U,Mo)Al conductivity	pH	oxidation model
0%	5 W/m·K (direct measurement of IL formed by ion irradiation)	6.0	Model 1
0%	10 W/m·K (approximated based on literature data)	6.0	

- The impact of IL thermal conductivity (TC) is through changing fuel meat TC.
  - Lower IL TC → higher fuel meat temperature
  - Peak fuel meat temperature appears at the BOC of the 3rd cycle, instead of BOL.
- Both codes agree with each other generally.





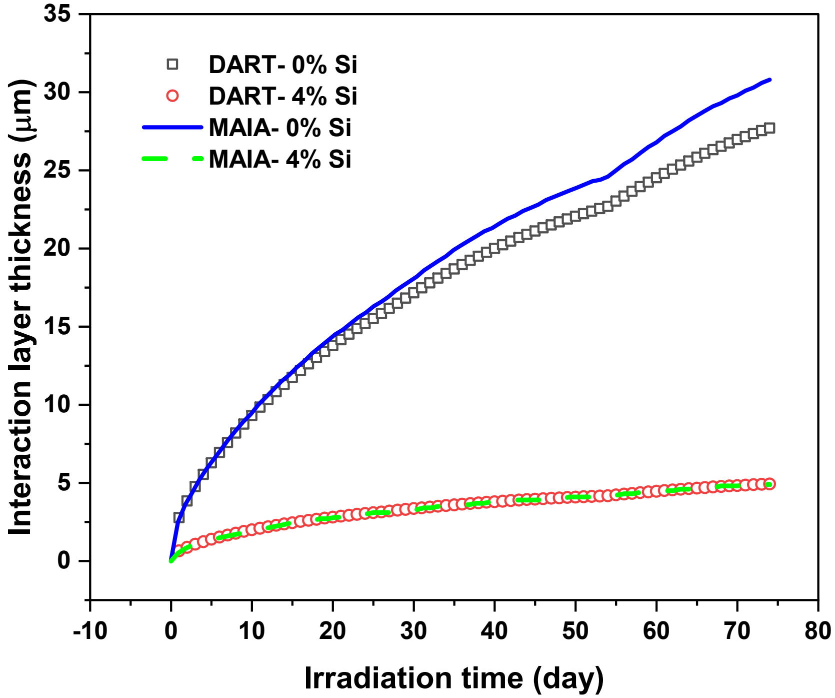
Calculation results were compared at the max fission density location.

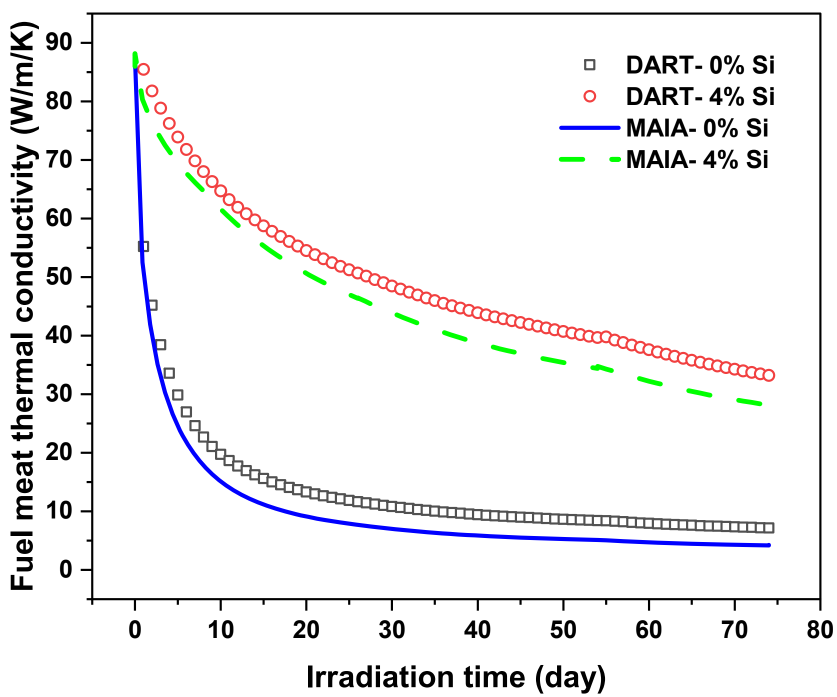
IMPACT OF SI CONTENT

- Si content → IL growth → IL volume fraction → fuel meat thermal conductivity
  - Higher Si content → less IL growth
  - Peak fuel meat temperature appears at the BOC of the 3rd cycle, instead of BOL.
- Both codes agree with each other generally.
  - The two codes use different fuel meat TC model. With the same IL thickness, meat TC is slightly different.

% Si	(U,Mo)Al conductivity	pH	oxidation model
0%	5 W/m·K	6.0	Model 1
4%	5 W/m·K	6.0	

Calculation results were compared at the max fission density location.



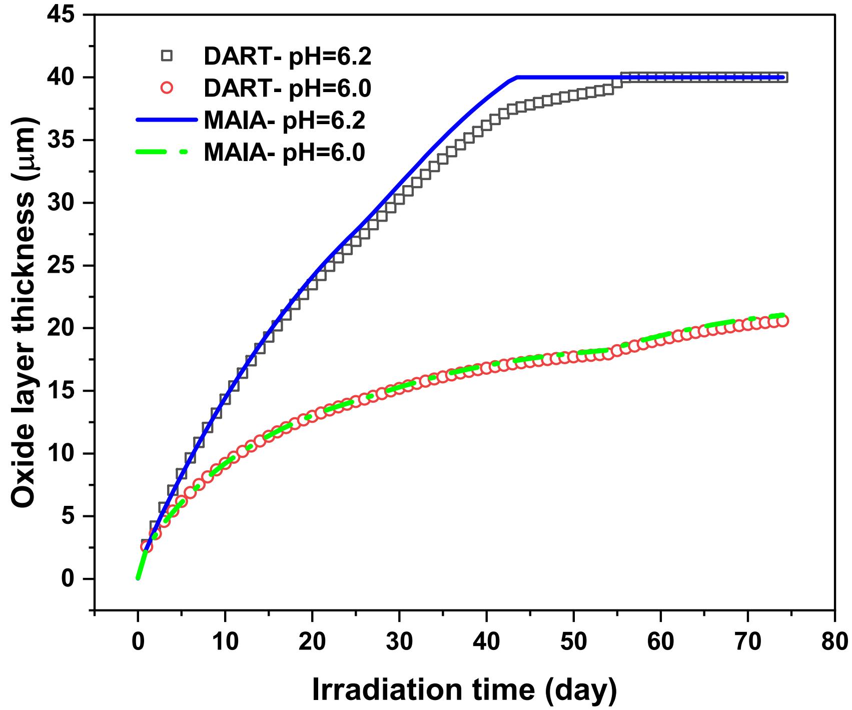


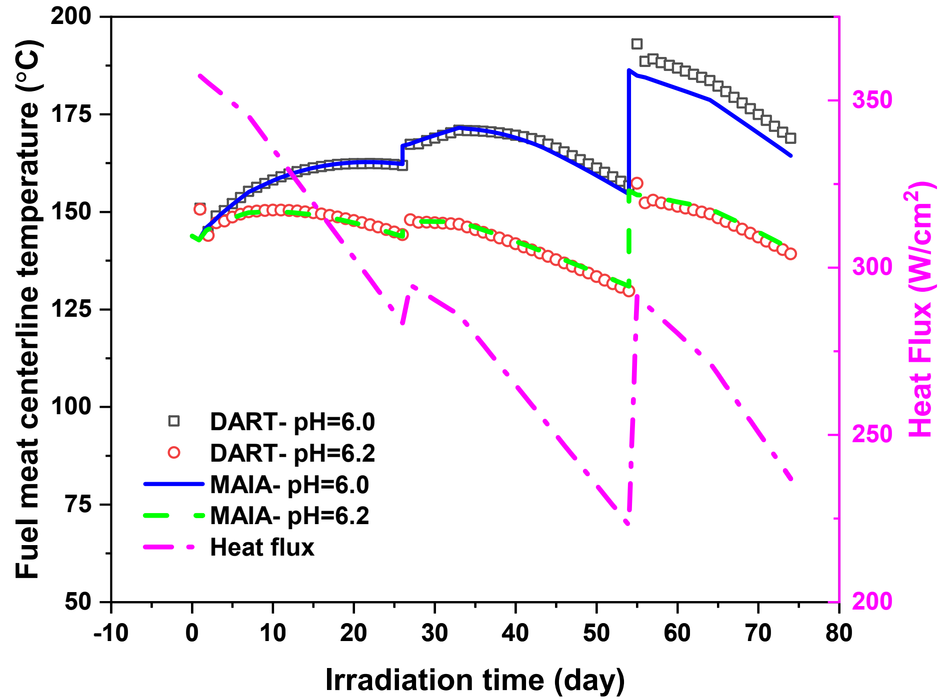
IMPACT OF PH VALUE

- pH value → oxide growth → fuel meat temperature
  - The model is sensitive to the pH value
- Both codes agree with each other generally.

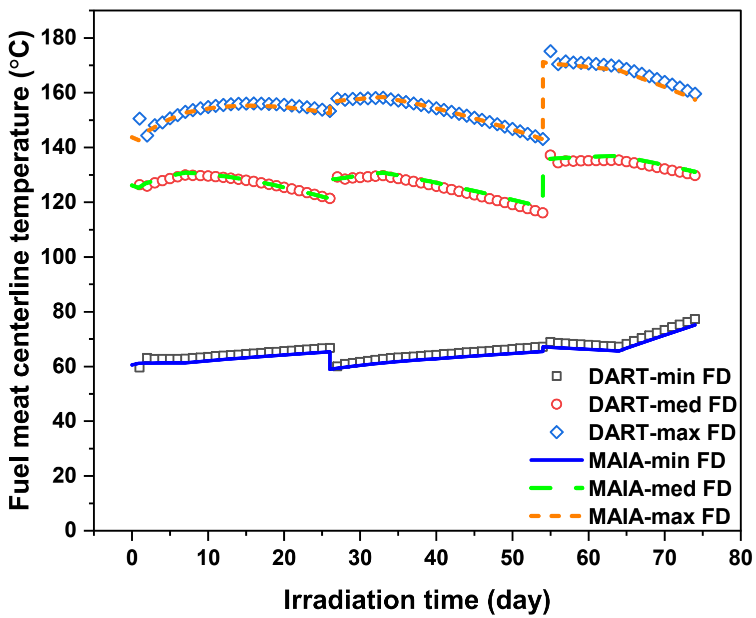
% Si	(U,Mo)Al conductivity	pH	oxidation model
4%	5 W/m·K	6.2	Model 1
4%	5 W/m·K	6.0	

Calculation results were compared at the max fission density location.





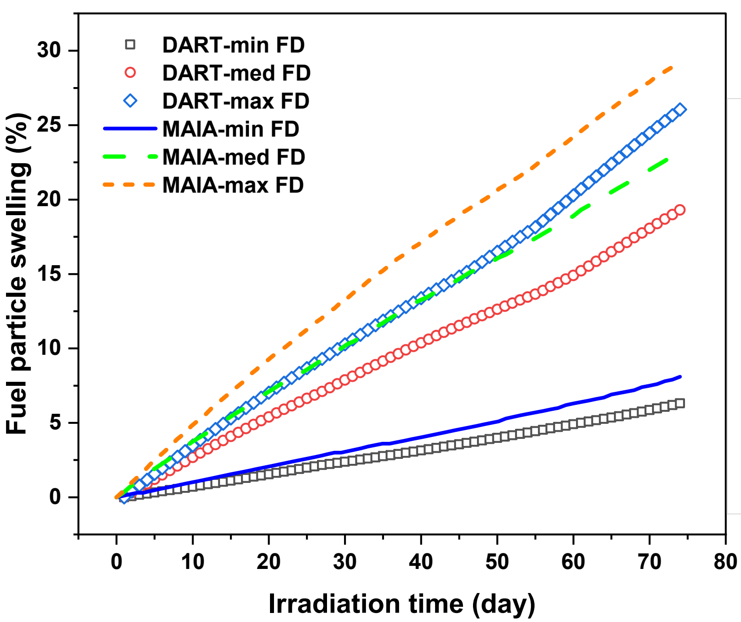
IMPACT OF FISSION DENSITY

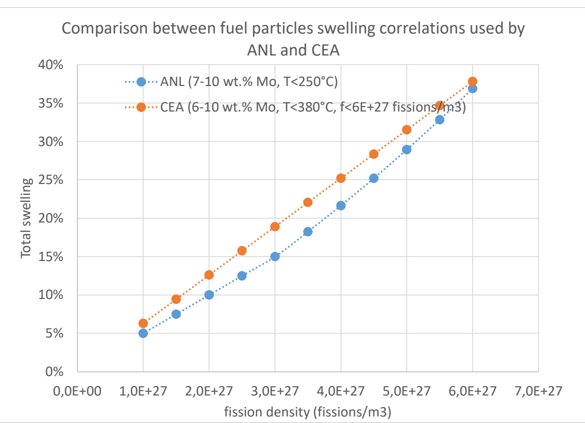


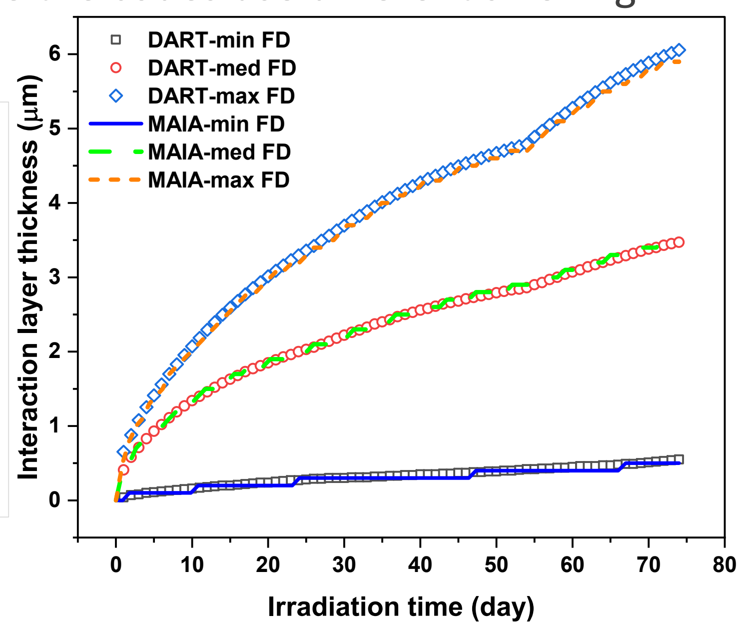
Calculation results were compared at all three fission density locations.

% Si	(U,Mo)Al conductivity	pH	oxidation model
4%	5 W/m·K	6.2	Model 2

- Max fission density location has the highest temperature, IL thickness, and swelling.
  - Fission rate → fuel meat temperature → IL growth
  - Swelling is a function of fission density.
- Both codes agree well for fuel meat temperature and IL thickness.
- Noticeable difference can be seen in fuel particle swelling comparison. Because the codes use different swelling models.







Phase-II comparison with experimental measurements

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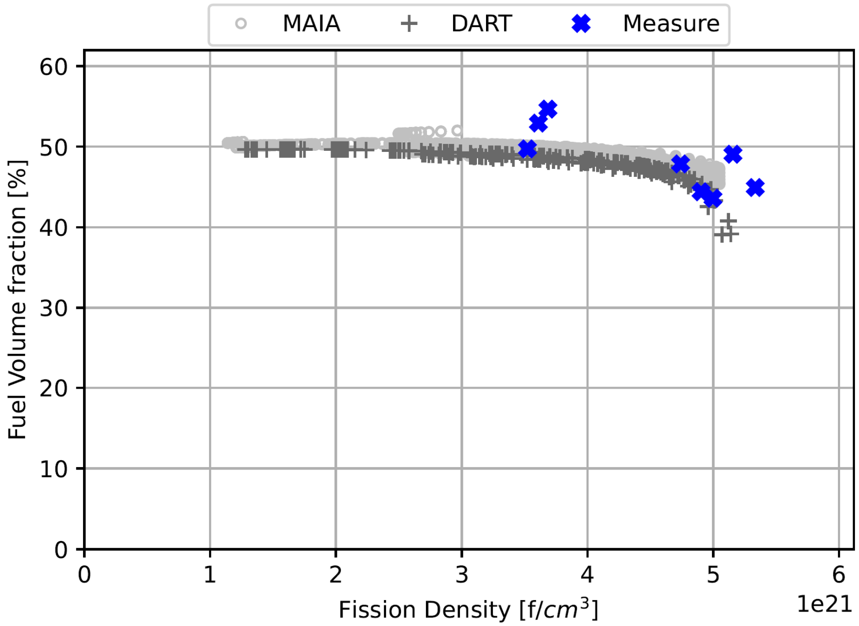
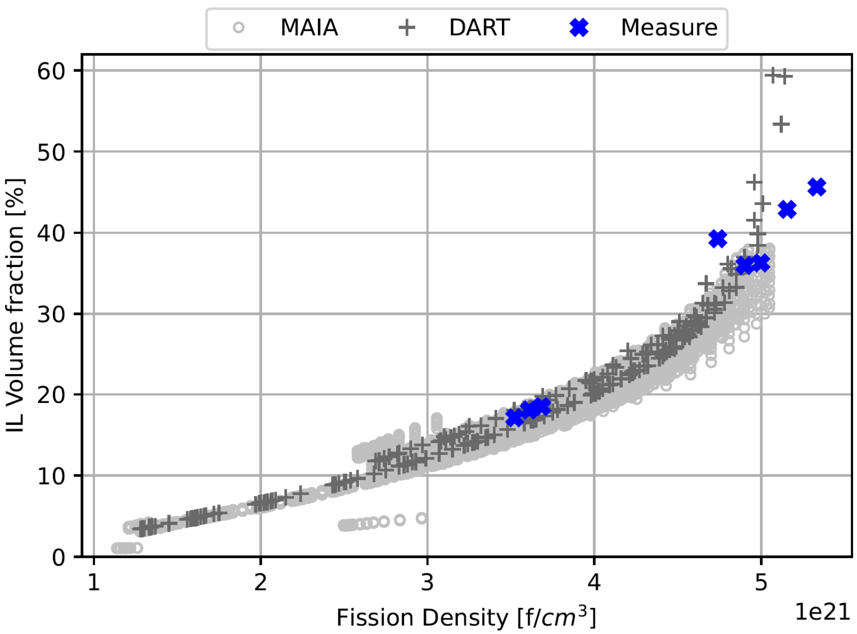
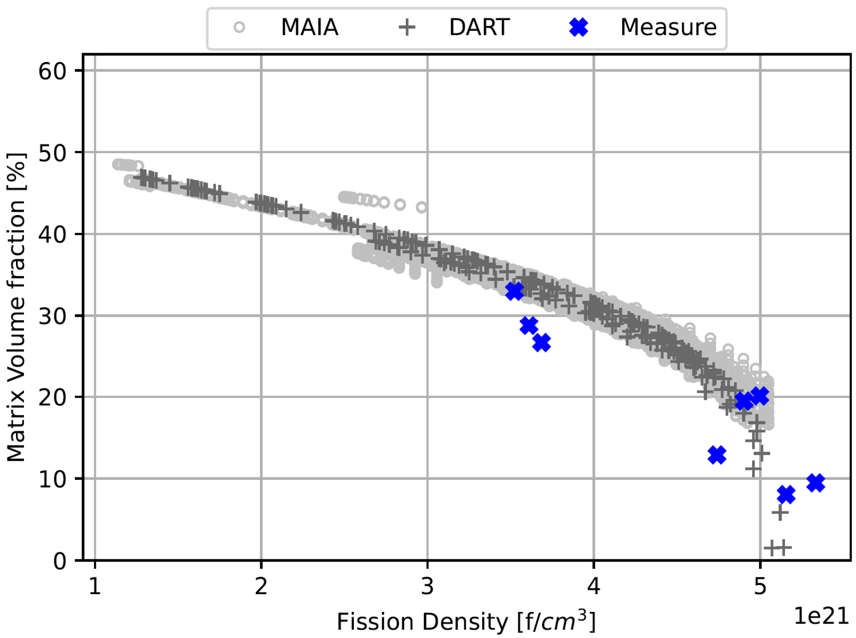
- **Measurement values (all slides)** : digitization of [JNM430] and [JNM441]
- **Codes / measurements comparison** : reasonable agreement, both in terms of absolute values and trend as a function of fission density
- **Hypothesis on the dispersion of the experimental values for very close fission densities**
  - heterogeneity of the fuel distribution in the meat
  - measurement uncertainties







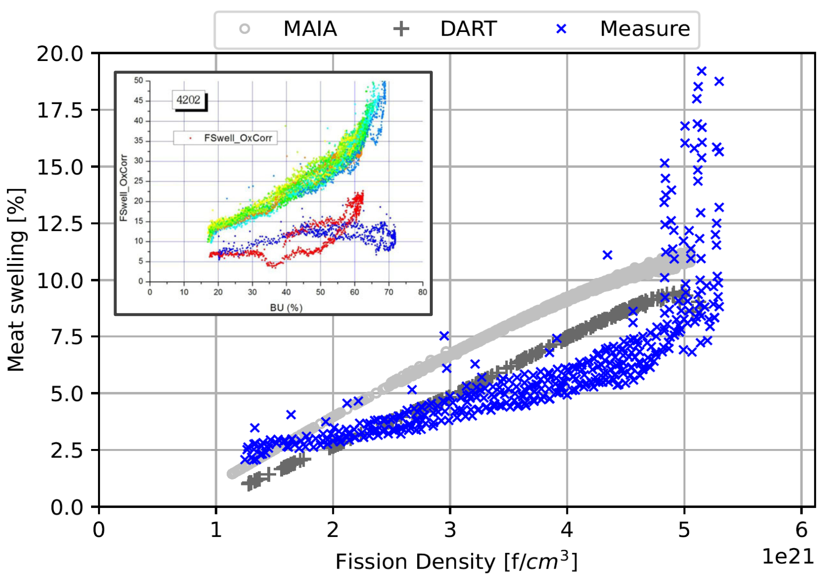
Fuel particle swelling

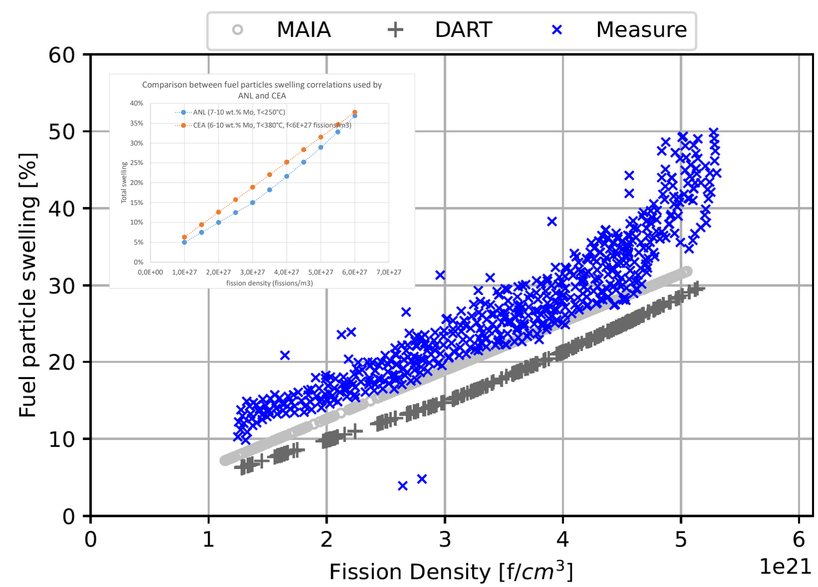
Remark : deletion of measurements made at the edges of the plate (edge effects : see [JNM430])

- ❑ Reasonable agreement
- ❑ Difference between MAIA and DART : different models used (reminder Phase-I)

Meat swelling

- ❑ Clear difference in slope between calculations and measurement. Hypothesis = conversion between fuel particle swelling and meat swelling
  - Experimental : nominal value of fresh fuel volume fraction ?
  - Calculation : homogenization method of the volume fractions of each component at each time step (fuel + matrix + interaction layer + pores closure)
- ❑ Remark : the extrapolation of the curves of the calculations do not pass by zero : related to the assumption of pore closure at the beginning of life

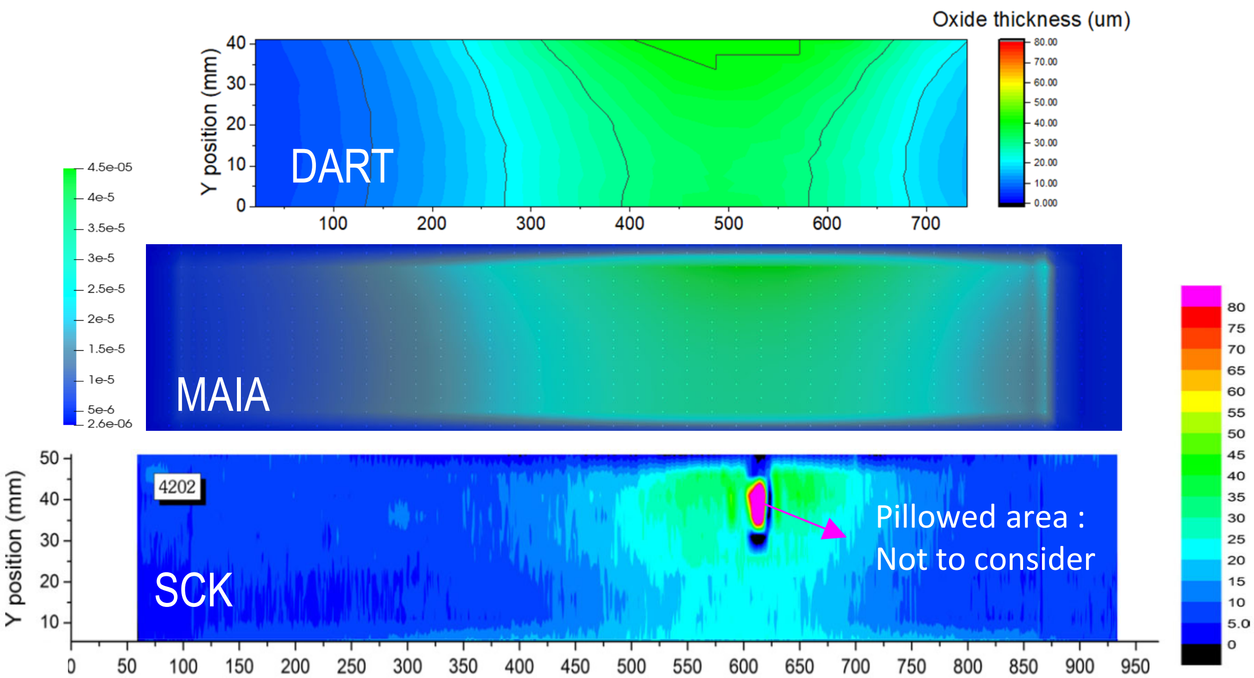


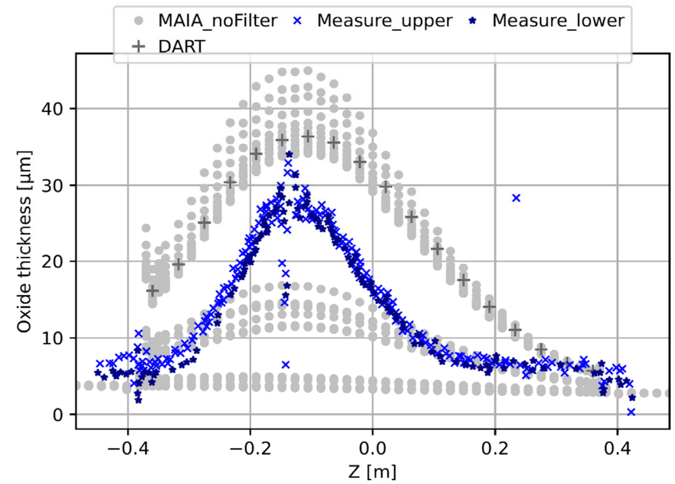


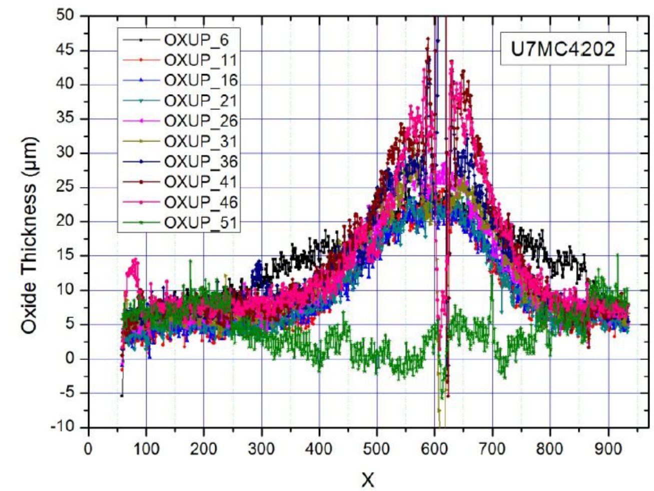
OXIDE THICKNESS

- **DART & MAIA results : values seem higher than the measurements : OK normal**
  - ❑ Plotted measurements = average values over the width of the plate
  - ❑ [JNM529] correlation calibrated on lines 41 and 46 (conservative approach)
  - ❑ Comparison between calculations and measurements lines 41 and 46 : correct agreement*

- **About plate edges effect**
  - ❑ Edge effects (lines 6 & 51) attributed in [JNM430] to influence of the edges on eddy current (“aberrant values”). Perhaps rather related to the strong thermal gradient at the edges of the plate ? see curves & 2D mapping*   *to verify more precisely, calculations with a higher mesh refinement on the plate edges should be performed)







Summary and future work

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SUMMARY AND FUTURE WORK

Agreement between the codes

- General agreement for all parameters compared.
  - In many cases, the results are identical.
  - Small discrepancies are observed for fuel meat/fuel particle swelling and fuel meat thermal conductivity comparisons, which are due to different models implemented in the two codes for calculating swelling and fuel meat thermal conductivity.
- The parametric study show that
  - Fuel meat temperature is sensitive to oxide growth model, IL thermal conductivity, pH value, and Si content in the matrix.
  - Fuel meat temperature reached the peak value at the beginning of the 3^{rd} cycle when the heat flux was lower than that at the BOL, because of the degradation of fuel meat thermal conductivity.

Agreement between calculated and measured results

- Reasonable agreement for all parameters considered
- Strong assumptions about the origin of the discrepancies
- These preliminary results will have to be iterated with the experimenters

Future work

- Benchmark on SEMPER-FIDELIS (UMo coated particles)
- Benchmark on silicide fuel

The development of reliable fuel performance simulation tools supports the development and qualification of RTR fuels required for reactor conversion from HEU to LEU.

THANK YOU FOR YOUR ATTENTION

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