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Best estimates plus uncertainty analysis for the ^{244}Cm prediction in spent fuel characterization

BEPU conference, 13-18 May 2018, Lucca, Italy

Summary

- Introduction/Motivations

- Samples (U1 and U2)
- Calculation tools

- Possible biases from the irradiation history

- Uncertainty on isotopic inventory
  - Nuclear data
  - Operating conditions
  - Manufacture tolerances
  - Burnup-induced Technological changes

- Conclusions

Introduction/Motivations

1. Spent Nuclear Fuels (SNF) need to be characterized with a sufficient level of confidence for transport + storage
   – Understanding of the measurements (if any)
   – Understanding of the calculation procedure
   – Estimation of possible C/E
   – Estimation of experimental and calculated uncertainties + biases

2. Post Irradiation Examination (PIE) play a crucial role in the validation of the calculation scheme for SNF inventory
   – SFCOMPO database, MALIBU, ARIANE, LWR-PROTEUS

3. PIE for 2 LWR-PROTEUS samples will be analyzed in this work
   – Estimate C/E
   – Estimate the impact of inputs (nuclear data, operating conditions…)
   – Estimate the effect of irradiation histories
   – Emphasize will be put on ^{244}Cm (important neutron emitters during transport and short-term storage)

Samples and Calculation tools

- LWR-PROTEUS samples:
  - U1 and U2 (37 and 54 MWd/kgU)
  - Irradiated in Gosgen (PWR), 2 and 3 cycles, respectively,
  - UO_2 fuel, 4.1 and 3.5 % ^{235}U
  - PIE measurements (actinides and fission products)
  - Many previous analysis based on CASMO + SNFlight

- Calculation tools:
  - Lattice calculations: CASMO-5MX,
  - Irradiation history
    1. Simplified from operator
    2. Detailed based on core follow-up analysis with CASMO/SIMULATE
  - Nuclear data sampling: SHARK-X (CASMO-5MX+ ENDF/B-VII.1 random sampling)

Irradiation history

- Simplified or detailed irradiation history for the (1) sample power, (2) fuel & moderator temperatures, (3) boron concentration and (4) burn-up steps
- Example for U2:

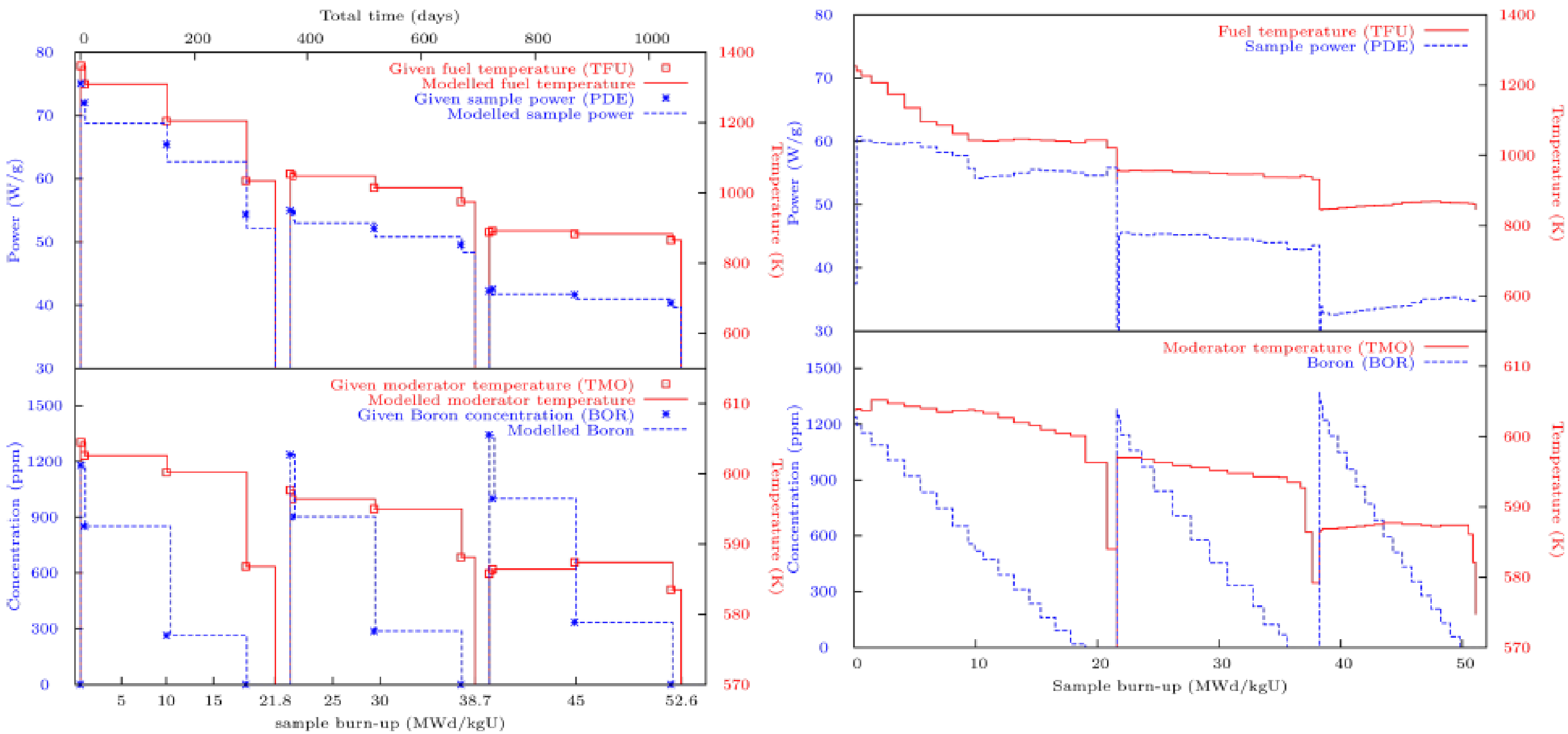

Figure 1 – Left: Four main CASMO parameters used in Ref. [7] for the U2 sample. Right: same parameters obtained with the detailed history, extracted from SIMULATE).

Effect of the irradiation histories

- Effect of the simplified and detailed irradiation histories
- With Adjustment of ^{148}Nd C/E within the experimental uncertainties

Table 1 – Summary of the results obtained in this work for ^{244}Cm and for the considered samples (U1 and U2). See text for the terms "simplified" and "detailed history".

Sample name	Enrichment fissile (wt %)	Burn-up simplified history (MWd/kgU)	Burn-up detailed history (MWd/kgU)	Burn-up variation %	^{244}Cm C/E-1 simplified history (%)	^{244}Cm C/E-1 detailed history (%)
U1	4.1	37.6	35.8	-5	+25	-3.4
U2	3.5	54.3	52.3	-4	+14	-0.7

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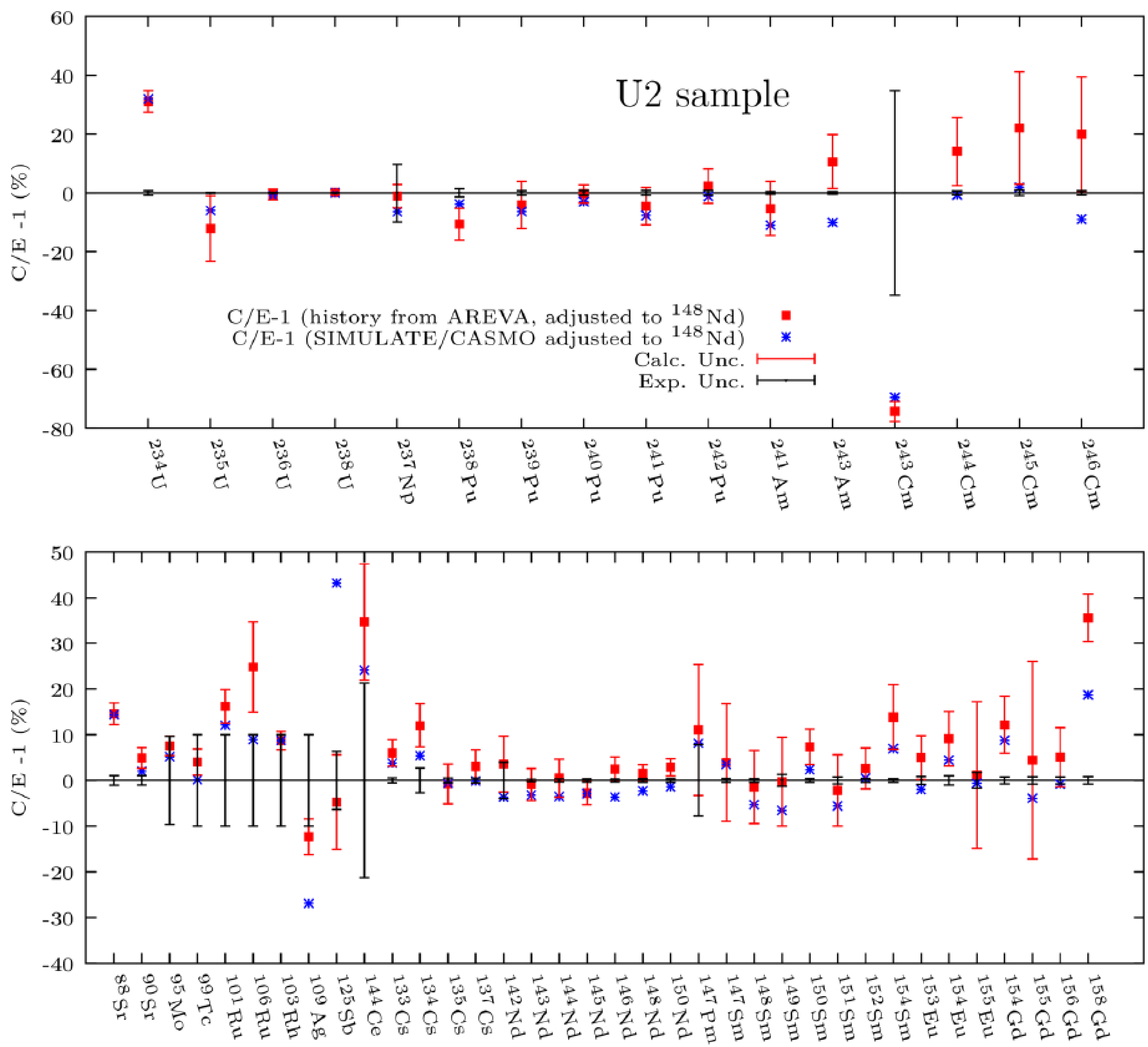
Uncertainty and biases for PIE C/E



Details of the input variations (1/2)

- Nuclear data: all ENDF/B-VII.1 isotopes with covariance information (sampling method) + ad-hoc fission yield covariance matrices.
  - Major actinides: ^{235,238}U and ^{239}Pu,
  - Light elements: ^{1}H, ^{10,11}B, ^{16}O and ^{nat}C,
  - Structural materials: $^{28-30}$Si, ^{59}Co,^{58}Ni, ^{54,56,57}Fe, ^{50,52,53}Cr, ^{90,91,92,94,96}Zr,
  - Heavy isotopes: $^{152,154-158,160}$Gd, ^{182,183,184,186}W,
  - Minor actinides: ^{234,236}U, $^{235-239}$Np, $^{236,238,240-242,244}$Pu, ^{241,243}Am, $^{242-244}$Cm,
  - Fission products: ^{95,98,100}Mo, ^{99}Tc, $^{101-103,106}$Ru, ^{109}Ag, ^{127,129}I, ^{131,134}Xe, ^{133,135}Cs, ^{135}La, ^{139}Ce, ^{141,143,145}Nd, ^{148}Pm, ^{153,155}Eu.
- Operating conditions:

Table 3 – Uncertainties and probability density functions for the operating conditions considered in this work ("U" means uniform and "N" normal probability density function). σ is the standard deviation (uncertainty) of the distribution.

	Fuel Temp.	Moderator Temp.	Reactor Pressure	Boron Conc.	Irradiation history
CASMO keywords	TFU	TMO	PRE	BOR	DEP
Standard deviation (σ)	2 % U	2 % U	1 % U	2 % U	1 % U

Details of the input variations (2/2)

- Manufacture tolerances

Table 4 – Uncertainties and probability density functions for the 7 manufacturing conditions considered in this work ("U" means uniform and "N" normal probability density function).

	Pin radius	Fuel pin position shift	Guide thimble shift	Fuel density	^{235}U enrich.	^{234}U enrich.	^{238}U enrich.
CASMO keywords	R	LDX/Y	LDX/Y	FUE D	W5	W4	W8
	0.5 % U	1 mm	0.2 mm	1.5 % U	0.2 % U	correlated with W5	correlated with W5

- Burnup induced Technological Changes:
  - Fuel Pin position shift: 0.2 mm/burn-up groups (uniform),
  - Moderator Pin position shift: 0.05 mm/burn-up groups (uniform),
  - Pellet diameter increase: 150 μm at 53 GWd/t.

Results of uncertainties for ^{244}Cm

Table 2 – Uncertainties in % on the ^{244}Cm concentration at the time of the PIE measurements, due to specific inputs. The total uncertainties are calculated as a simple quadratic sum with correlation terms.

Sample name	Nuclear data	Operating conditions	Manufacturing tolerances	Burn-up induced	Total
U1	8.6	3.8	2.7	5.0	10.2
U2	9.6	2.1	1.6	2.5	11.1

Conclusion

To conclude, the results for both U1 and U2 samples are summarized as follows for ^{244}Cm:

- Original results: C/E-1(U1)= +25 % and C/E-1(U2)= +14 %,
- Best estimate plus uncertainties: C/E-1(U1)= -3.4 % with a calculated uncertainty of 10.2 %; and C/E-1(U2)= -0.7 % with a calculated uncertainty of 11.1 %,

indicating that the C/E values do not show significant disagreement between the measurements and calculations ^{244}Cm concentrations, given the calculated uncertainties.

- Main contributor to the uncertainties: nuclear data
- Important effect of the irradiation history

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Wir schaffen Wissen – heute für morgen