FISA EURADWASTE 2025

SNETP Forum

Transposition Studies with a Hybrid Experimental Database

Eric Njayou[1], Patrick Blaise[2], David Couyras[1], Jean-Philippe Argaud[1], Laura Clouvel[1] and Nicolas Dos Santos[3]

[1]EDF Lab Paris-Saclay, 7 Boulevard Gaspard Monge, 91120 Palaiseau, France

[2]Framatome, DTIPDM-F, 2 rue Pr Jean Bernard, 69007 Lyon, France

[3]EDF Lab Chatou, 6 Quai Watier, 78400 Chatou, France

Introduction

The qualification of calculation tools used in the safety demonstration of nuclear reactors is based on a three-stage process: Verification, Validation and Uncertainty Quantification, known as VV&UQ. For current reactors, the last two stages are mainly based on computational-experimental comparisons. The latter are therefore limited in cases where measurements are not available (new fuel management, new concepts, accident situations, etc.). Transposition is a way of overcoming this limitation. Its principle consists in extrapolating validation results from one operating domain (validation domain) to another, not covered by experience (validity domain). This approach also helps to reduce calculation uncertainties.

Transposition by Bayesian inference : state-of-the-art

Uncertainty propagation

Deterministic propagation using the method of moments, also known as the sandwich rule

$$\varepsilon = \sqrt{SDS^T}$$

- $\boldsymbol{D}$ is the covariance matrix between the nuclear data
- $\boldsymbol{S}$ is the sensitivity vector of the output with respect to the nuclear data, calculated from the first order perturbation theory (SPT, GPT).

Data assimilation (DA)

Adjustment of the prior input parameters of the model by Bayesian inference, from the knowledge given by a likehood model constituted by the measurements. The adjusted posterior parameters allow a more precise calculation and a better computational-experimental consistency.

Representativity and transposition

Extrapolation of the information issued from the measurements (DA) of one or several experiments (*exp*), to an application case (*app*).

Example of the mathematical formulation for one experiment :

$$\begin{cases} \dfrac{\tilde{C}_{app}-C_{app}}{C_{app}} = \left(\boldsymbol{r} * \dfrac{\varepsilon_{app}}{\varepsilon_{exp}} * \dfrac{1}{1+\frac{\delta E^2}{\varepsilon_{exp}^2}} \right) * \left(\dfrac{E-C_{exp,0}}{C_{exp,0}}\right) \\ \tilde{\varepsilon}_{app} = \varepsilon_{app} \sqrt{1 - \dfrac{r^2}{1+\frac{\delta E^2}{\varepsilon_{exp}^2}}} \end{cases}$$

$C_{x,0}$, ε_x: prior output and uncertainty
$\tilde{C}_x$, $\tilde{\varepsilon}_x$: posterior output and uncertainty
δE: experimental uncertainty
E: measurement

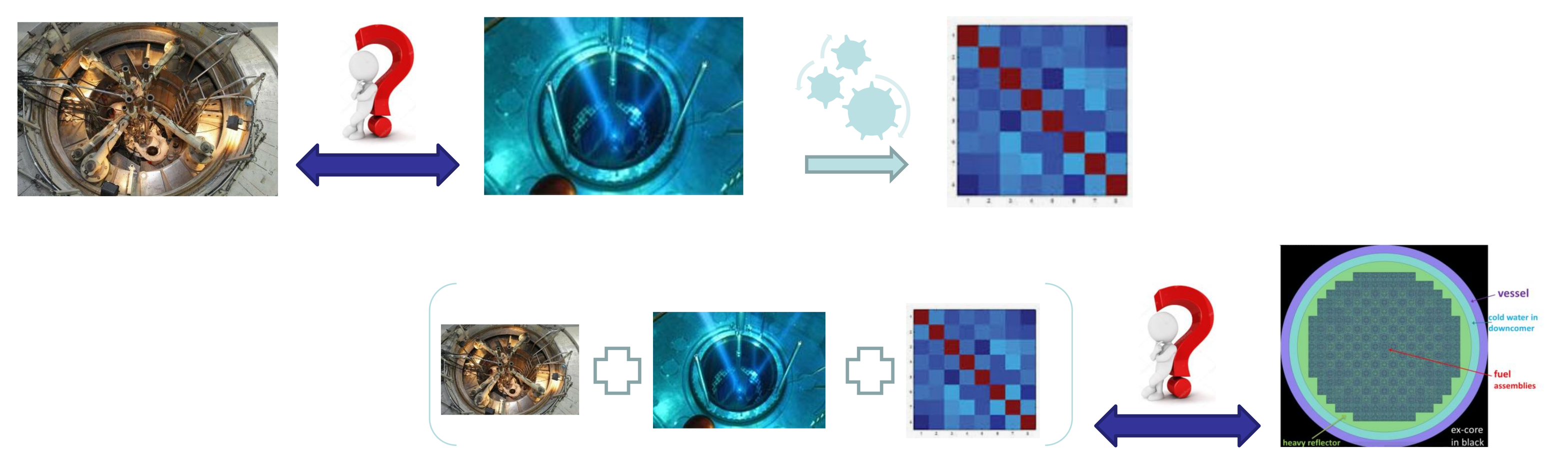
Two fundamental indicators determine the transferability of the assimilated information:

✓ the representativity coefficient (r), measures the correlation between the experiment and the application case in the nuclear data point of view.

$$r = \frac{S_{exp}\boldsymbol{D}S_{app}^T}{\sqrt{S_{app}\boldsymbol{D}S_{app}^T} * \sqrt{S_{exp}\boldsymbol{D}S_{exp}^T}}$$

✓ The *experimental uncertainty / nuclear data uncertainty* ratio on the experiment $\left(\frac{\delta E}{\varepsilon_{exp}}\right)$

In the case of several experiments in the *experimental database*, a third indicator is to consider: the matrix of experimental correlations ($\boldsymbol{M_E}$).

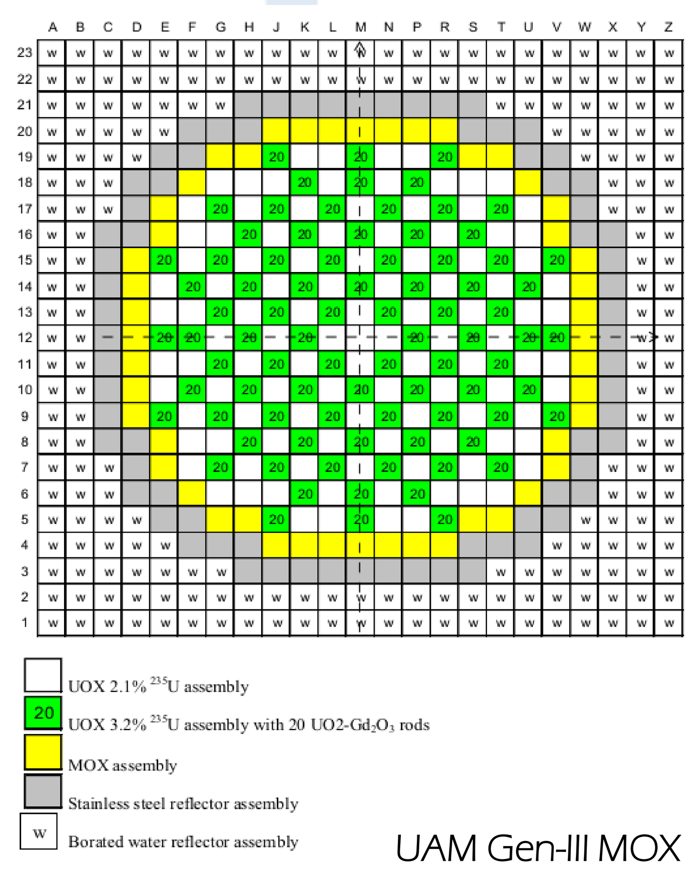


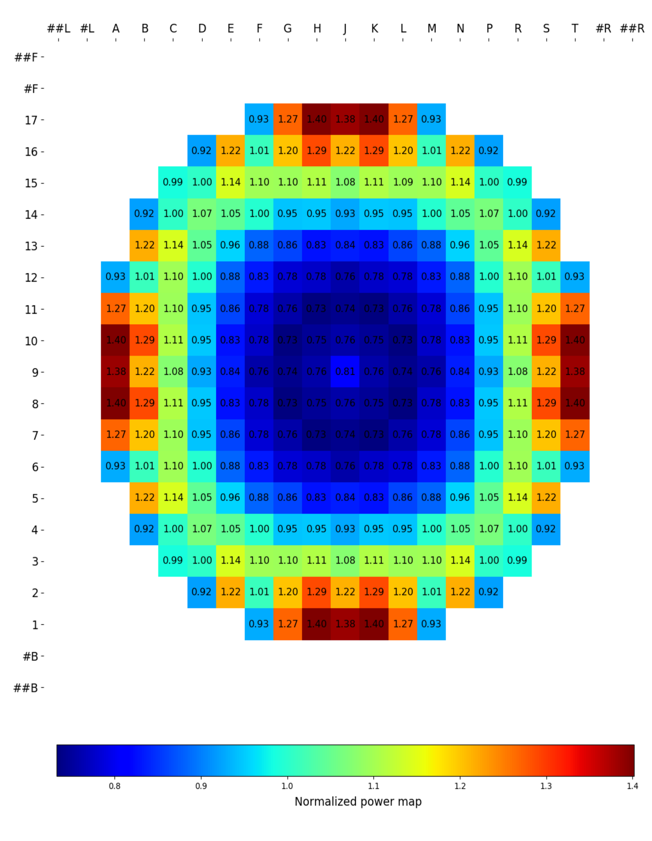
Description of the hybrid experimental data base

Mock-up experiments: UH1.4, UH1.4-ABS, UMZONE, CAMELEON-25GT-12GD

NPP measurements: First start-up configuration cores - BU2, DA1, CA4, CZ1 at zero power + full power depletion calculation for some configurations (CA4).

Application case: centre / periphery fission rate ratio (τ_f) of the UAM Gen-III MOX configuration (GEN III core with MOX assemblies at the periphery).





UAM Gen-III MOX

Experimental uncertainties and correlations estimation

$$\begin{cases} \delta E_i^{\,2} = \varepsilon_{techno}^{\,2} + \varepsilon_{mesure}^{\,2} = S_{tech,i}\underline{M_{tech}}S_{tech,i} + \varepsilon_{mesure}^{\,2} \\ r_{1,2}^{exp} = \dfrac{S_{tech,1}\underline{M_{tech}}S_{tech,2} + \delta_{technique\ 12}^{\,2} + \delta_{instru\ 12}^{\,2}}{\delta E_1 * \delta E_2} \end{cases}$$

The NPP measurements are mostly decorrelated and are decorrelated from the mock-up measurements. The latter share a large part of the fuel and are therefore very strongly correlated, as indicated below.

Experimental correlations

		BU2	DA1	CZ1	CA4		CA4(5)		UH1.4		UH1.4-ABS		UMZONE		CAMELEON	
		cb	cb	cb	cb	Ratio	cb	Ratio	cb	Ratio	cb	Ratio	cb	Ratio	cb	Ratio
BU2	cb	1	0.27	0.26	0.26	0	0.27	0	0.18	0	0.22	0	0.16	0	0.16	0
DA1	cb		1	0.26	0.26	0	0.26	0	0.18	0	0.22	0	0.16	0	0.16	0
CZ1	cb			1	0.25	0	0.26	0	0.17	0	0.22	0	0.16	0	0.16	0
CA4	cb				1	0.26	**0.51**	0	0.17	0	0.22	0	0.16	0	0.15	0
	Ratio					1	0	**0,58**	0	0	0	0	0	0	0	0
CA4(5)	cb						1	0.10	0.18	0	0.22	0	0.16	0	0.16	0
	Ratio							1	0	0	0	0	0	0	0	0
UH1.4	cb								1	0.07	**0.99**	0.05	**0.93**	-0.13	**0.99**	0
	Ratio									1	0.06	1	0.08	**0.86**	0.05	**0.97**
UH1.4-ABS	cb										1	0.04	**0.92**	-0.11	**0.97**	0
	Ratio											1	0.05	**0.85**	0.04	**0.98**
UMZONE	cb												1	0.06	**0.9**	0
	Ratio													1	-0.17	**0.82**
CAMELEON	cb														1	0
	Ratio															1

UAM-MOX prior uncertainty break down – zero power

The U235 spectrum, the Pu239 fission cross section and the U235, Pu239, Pu240 and Pu242 capture cross sections are the main contributors to the uncertainty of the fission rate ratio.

centre / periphery fission rate ratio (R = 0.85)					
Data	Uncertainty	% variance	Data	Uncertainty	% variance
U235_spectrum_1	13.0%	46%	Pu242_capture_5	5.3%	8%
U235_spectrum_3	-8.7%	-21%	Pu239_fission_7	5.0%	7%
U235_spectrum_4	-7.8%	-16%	U235_capture_5	4.9%	7%
Pu240_capture_6	6.2%	10%	U235_nu_8	4.5%	6%
Pu239_capture_7	5.4%	8%	Pu239_fission_5	4.5%	6%
Total	19.2%				

Transposition results and nuclear data adjustment

- Data assimilation from the experimental database results in a posterior value of the centre/periphery fission rate ratio of 1.03 (prior = 0,85) and a posterior uncertainty of 5,7% (prior = 19,2%), i.e. a reduction of about 70%.
- Significant in nuclear data nominal values and uncertainties among the main contributors.

Data (σ)	Delta σ	Prior Unc.	Posterior Unc.	Delta Unc.
U235_spectrum_1	9.9%	5.1%	2.9%	-43%
U235_spectrum_3	-5.9%	3.2%	1.8%	-44%
U235_spectrum_4	-15.9%	6.9%	4.1%	-41%
Pu240_capture_6	-16.3%	2.4%	1.4%	-42%
Pu239_capture_7	8.8%	2.5%	1.8%	-28%
Pu242_capture_5	28.3%	11.6%	9.6%	-17%
Pu239_fission_7	2.0%	1.5%	1.2%	-20%
U235_capture_5	-16.9%	8.6%	5.8%	-33%
U235_nu_8	0.8%	0.3%	0.3%	0%
Pu239_fission_5	0.8%	2.0%	1.8%	-10%

group 1 : fast
group 8 : thermal

Conclusions and outlook

Conclusions:

- Most of the REX measurements are decorrelated from each other and from measurements in critical mock-ups. In addition, the experimental uncertainty / nuclear data uncertainty ratios are generally low.
- The hybrid experimental database led to a significant reduction in the uncertainty due to the nuclear data: of the order of 70% on the centre / periphery fission rate ratio of the UAM Gen-III MOX configuration under the assumptions formulated.
- The posterior trends obtained from nuclear data can be used to suggest improvements in the ND libraries.

Outlook:

- Diversification of the experimental database with the introduction of new measurements targeting particular nuclear data (Fe56 for example)
- Application to real cases of NPP cycles (e.g., new fuel management on existing reactor).
- Evaluation of the impact of the implicit effect of resonances on nuclear data sensitivities.
- Evaluation of the sensitivity of the transposition results to experimental uncertainties and correlations.
- …

References

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11th European Commission Conference on EURATOM Research and Training in Reactor Safety & Radioactive Waste Management

12-16 May 2025, Warsaw, Poland