

CIEMAT activities on Benchmarking and Nuclear Data Validation using ICSBEP and IRPhE

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**Now at SCK CEN*



Validation of calculational methodologies and nuclear data regarding reactor kinetics parameters:

$$\frac{\partial}{\partial t} n(t) = \frac{\rho - \beta_{eff}}{\Lambda_{eff}} n(t) + \sum_j \lambda_j c_j(t) + S(t)$$

Effective delayed neutron fraction

Effective mean neutron generation time

1. V. Bécares *et al.*, “Review and comparison of effective delayed neutron fraction calculation methods with Monte Carlo codes”, Ann. Nucl. Energy 65 (2014) 402-416.
2. EU H2020 **SANDA** (Supplying Accurate Nuclear Data for energy and non-energy Applications) project **task 4.4**:
 - “Whereas nuclear data validation has been in the recent years mostly restricted to critical benchmarks, this effort will also focus on other types of measurements, such as shielding benchmarks and *kinetics*”.
 - “For criticality and *kinetic parameters*, a review of different suites of inputs used in ICSBEP will be performed, with selection/classification of benchmarks for different levels of nuclear data sensitivities, for benchmarking and validation of nuclear data”.
 - SANDA D4.6 “Report on the applications: recommendation” (in preparation).

β_{eff} and Λ_{eff} in ICSBEP and IRPhE

- IRPhE contain experimental kinetics parameter information only for 6 systems:

The screenshot shows the IDAT software interface with a search results table. The table has columns for Evaluation identification, Organisation/Laboratory, Title, and # matching cases. The results are as follows:

Evaluation identification	Organisation/Laboratory	Title	# matching cases
BFS1-LMFR-EXP-001	IPPE	BFS-73-1 ASSEMBLY: EXPERIMENTAL MODEL OF SODIUM-COOLED FAST REACTOR WITH CORE OF METAL ...	1
CROCUS-LWR-RESR-001	Lausanne	BENCHMARK ON KINETICS PARAMETERS IN CROCUS	6
IPEN(MB01)-LWR-RESR-001	IPEN	REACTOR PHYSICS EXPERIMENTS IN THE IPEN/MB-01 RESEARCH REACTOR FACILITY	1
ORSPHERE-FUND-EXP-001	ORNL	ORSPHERE: PHYSICS MEASUREMENTS FOR BARE, HEU(93.2)-METAL SPHERE	1
SNEAK-LMFR-EXP-001	Karlsruhe	SNEAK 7A AND 7B PU-FUELED FAST CRITICAL ASSEMBLIES IN THE KARLSRUHE FAST CRITICAL FACILITY	2

- Orsphere (^{235}U , fast) $\rightarrow \beta_{eff} \Lambda_{eff} \alpha$
- BFS1-73 (^{235}U , fast) $\rightarrow \beta_{eff}$
- SNEAK-7A & 7B (Pu, fast) $\rightarrow \beta_{eff}$
- IPEN/MB-01 (^{235}U , thermal) $\rightarrow \beta_{eff} \Lambda_{eff}$
- CROCUS (^{235}U , thermal) \rightarrow Inverse periods
- IRPhE, ICSBEP and literature search.
- S. Okajima *et al.*, Prog. Nucl. Energy 41 (2002) 285-301.
 - 2 MASURCA and 3 FCA benchmark experiments for β_{eff} .

Fuel	Spectrum	β_{eff}	Λ_{eff}
^{235}U systems	Fast & intermediate	13	3
	Thermal	2	1
Pu & mixed fuel systems	Fast & intermediate	10	1
	Thermal	---	---
^{233}U systems	Fast & intermediate	2	1
	Thermal	---	---
TOTAL		27	6

β_{eff} and Λ_{eff} calculation methods with MC

- Bretscher's (k-prompt) technique for β_{eff} :

$$\beta_{eff} \cong 1 - \frac{k_p}{k_{eff}}$$

k_{eff} calculated without delayed neutrons (MCNP TOTNU NO)

M. M. Bretscher, "Evaluation of reactor kinetic parameters without the need for perturbation codes", 1997 Intl. Meeting on Reduced Enrichment for Research and Test Reactors.

- Chiba's perturbative technique for β_{eff} :

$$\beta_{eff} \cong \frac{1}{\alpha} \left(\frac{k_{eff}}{k_{eff}} - 1 \right)$$

k_{eff} calculated by multiplying by $(\alpha + 1)$ the value of $\bar{\nu}_d$ in the nuclear data libraries

G. Chiba, "Calculation of Effective Delayed Neutron Fraction Using a Modified k-Ratio Method", J. Nucl. Sci. Technol. 46 (2009) 399-402.

- Perturbative technique for Λ_{eff} :

$$\Lambda_{eff} \cong \frac{1}{A} \frac{(\rho - \rho_c)}{N(c)}$$

ρ calculated introducing $N(c)$ at/cm³ of a fictitious isotope with an absorption cross section $\sigma_c = c/v$.

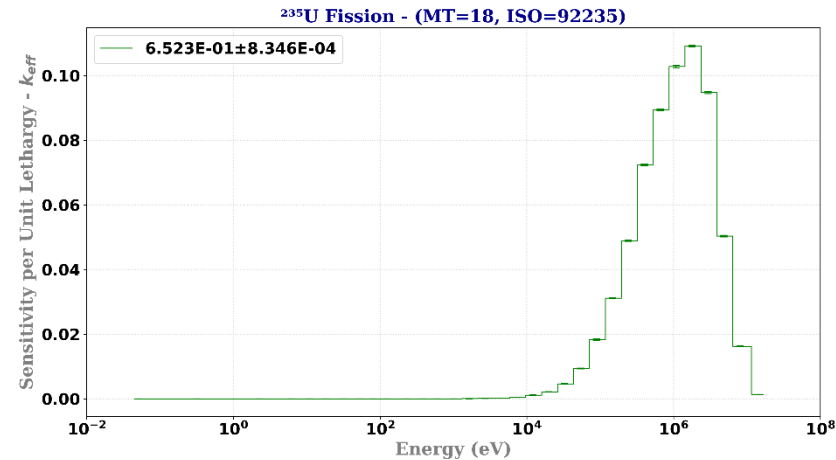
B. Verboomen *et al.*, "Monte Carlo calculations of the effective neutron generation time", Ann. Nucl. Energy 33 (2006) 911-916.

S/U analysis methodology (I)

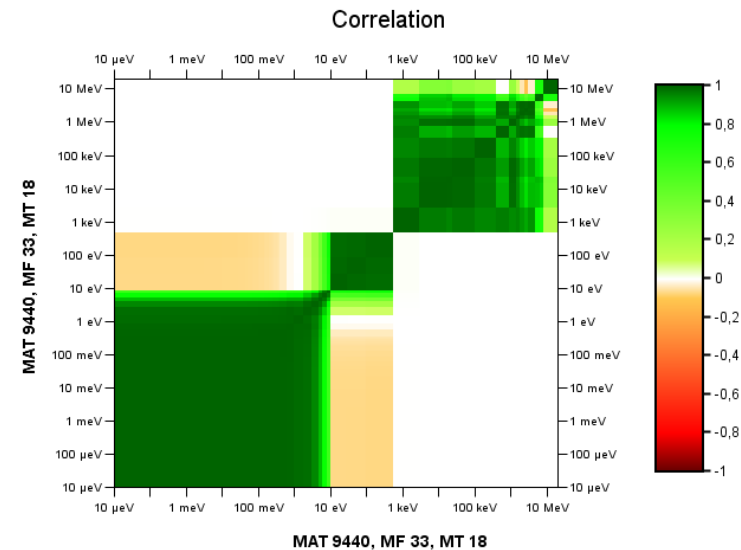
- **Sensitivity analysis** → quantifying the effect of a given variation in the input parameters (nuclear data) of a model in the calculation results.
- **Sensitivity coefficients and sensitivity profiles:**

$$S_{\alpha_i} = \frac{\alpha_i}{f} \frac{\partial f}{\partial \alpha_i}$$

- MCNP KSEN card.



- **Uncertainty analysis** → determining the uncertainty in calculation results due to the uncertainty in the input parameters (nuclear data).
- Uncertainty in nuclear data included in covariance matrices $Cov(\alpha_i, \alpha_j)$ included in the latest versions of nuclear data libraries.

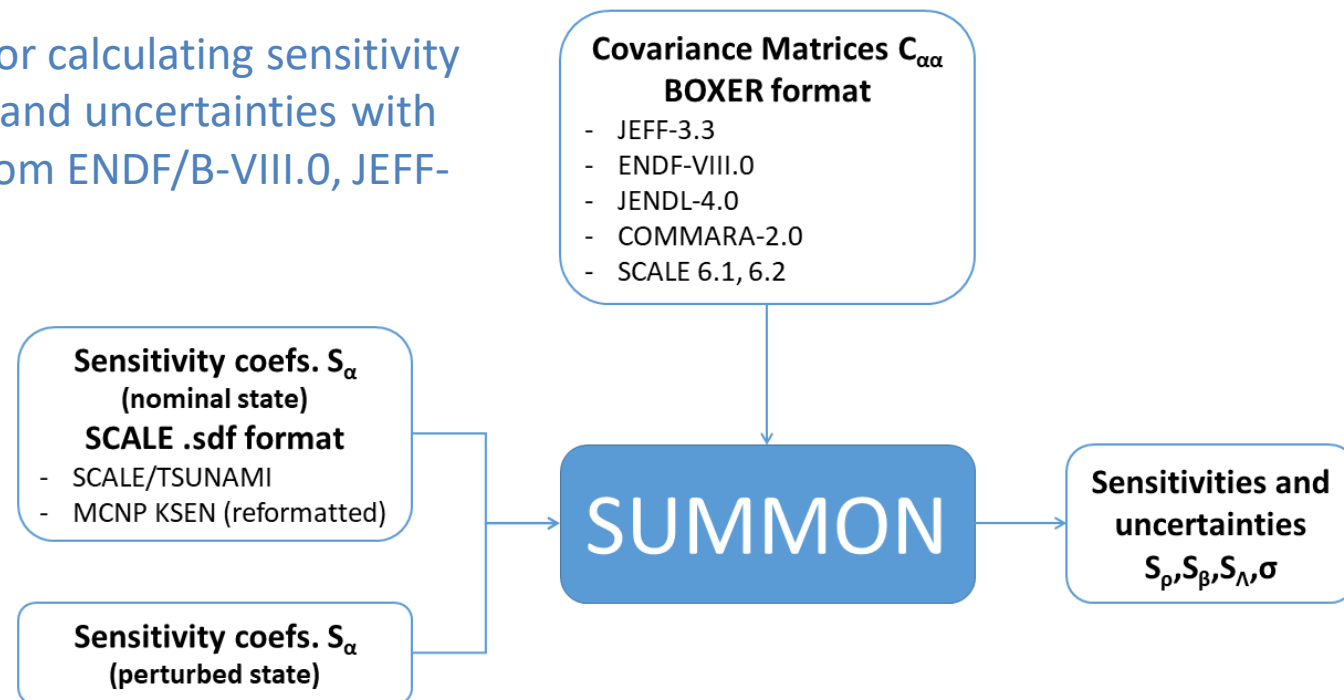


S/U analysis methodology (II)

- **Sandwich rule:**

$$\text{Var}(f) = \sum_i \left(\frac{\partial f}{\partial \alpha_i} \right)^2 \text{Var}(\alpha_i) + \sum_{i,j} \frac{\partial f}{\partial \alpha_i} \frac{\partial f}{\partial \alpha_j} \text{Cov}(\alpha_i, \alpha_j) = S_\alpha V_\alpha S_\alpha^T$$

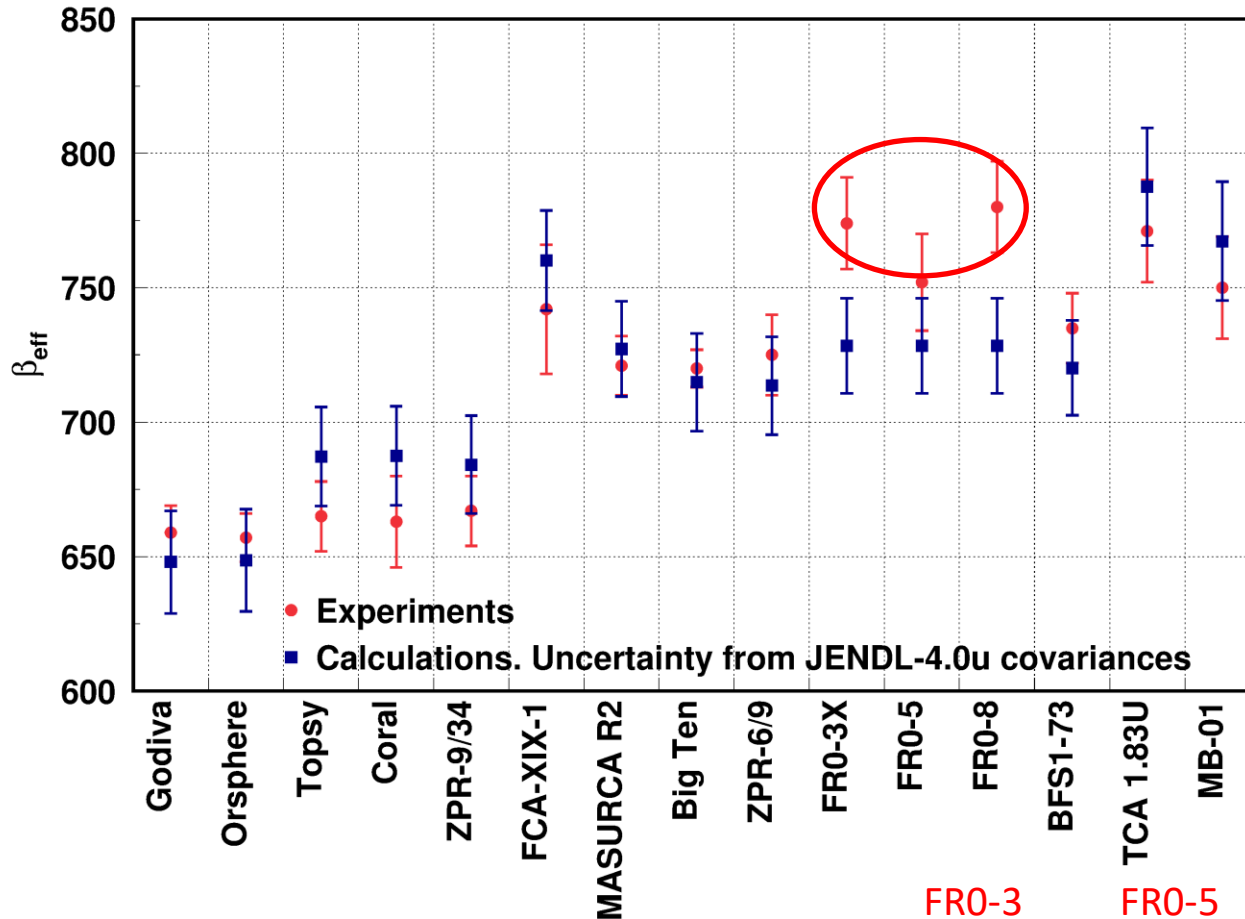
- SUMMON code used for calculating sensitivity profiles of β_{eff} and Λ_{eff} and uncertainties with covariance matrices from ENDF/B-VIII.0, JEFF-3.3 and JENDL-4.0u.



P. Romojarro *et al.*, “SUMMON: A Sensitivity And Uncertainty Methodology For MONte Carlo Codes”, Proceedings of International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2017), Jeju, Korea, 2017.

Validation results for β_{eff} (I)

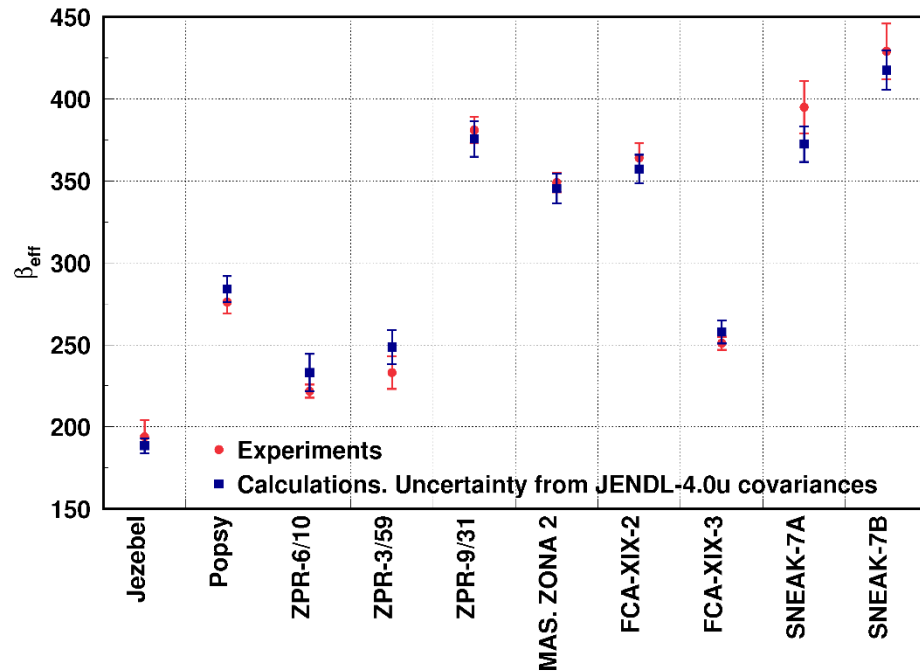
^{235}U systems:



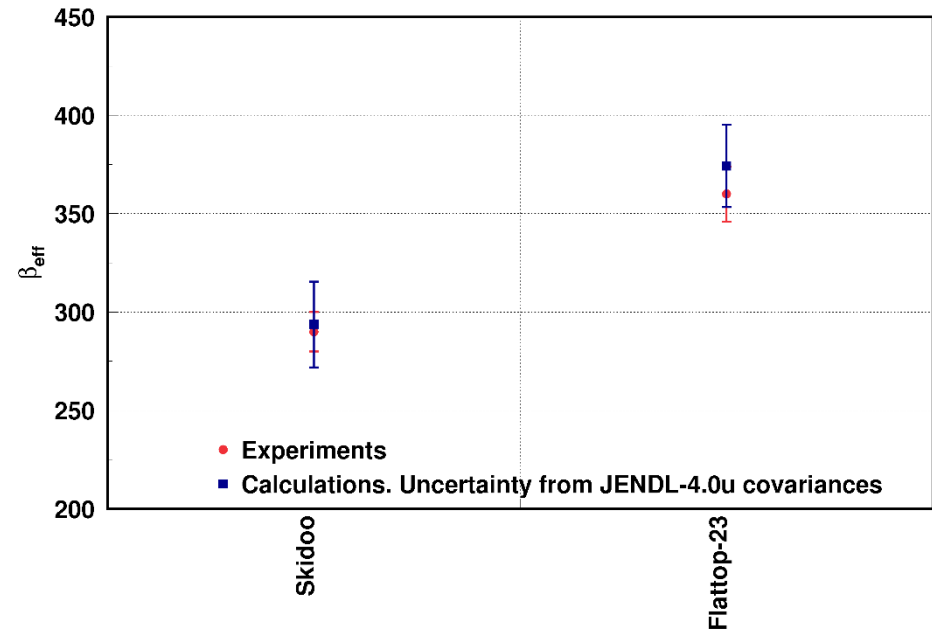
L. Moberg and J. Kockum, Atomenergi report AE-456, 1972.	719 ± 16	735 ± 18	735 ± 16
L. Moberg and J. Kockum, Nucl. Sci. Eng. 52 (1973) 343-349.	774 ± 17	752 ± 18	780 ± 17

Validation results for β_{eff} (II)

Pu & mixed fuel systems:



^{233}U systems:

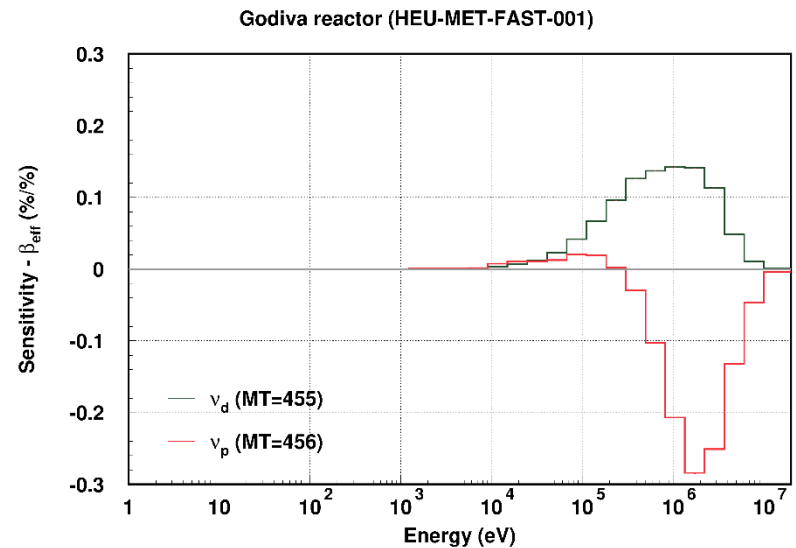
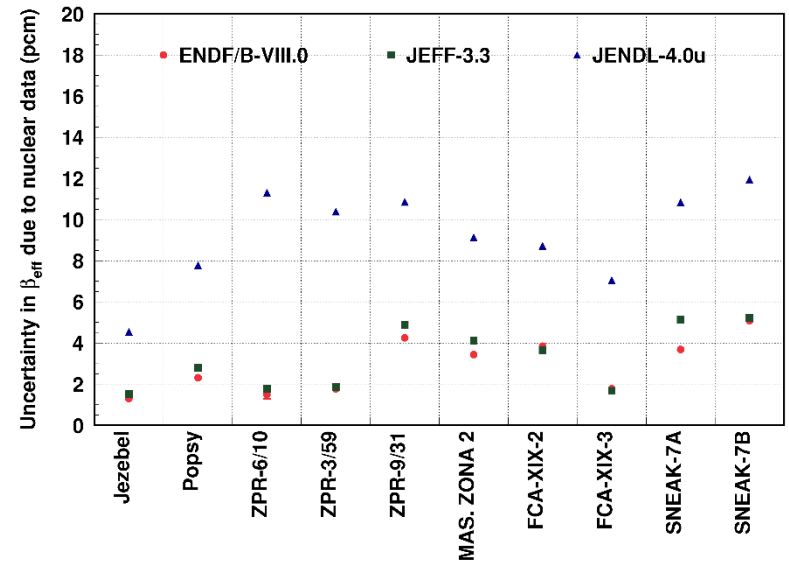


Validation results for β_{eff} (III)

- Remarks:
 - Uncertainty due to nuclear data depends largely on the covariance matrices.
 - Largest sensitivity to $\bar{\nu}_d$ of fissile isotopes.
 - Large negative sensitivity to $\bar{\nu}_p$, also observed in SUS3D calculations in I. Kodeli, NIMA 715 (2013) 70–78.

Godiva (HEU-MET-FAST-001)

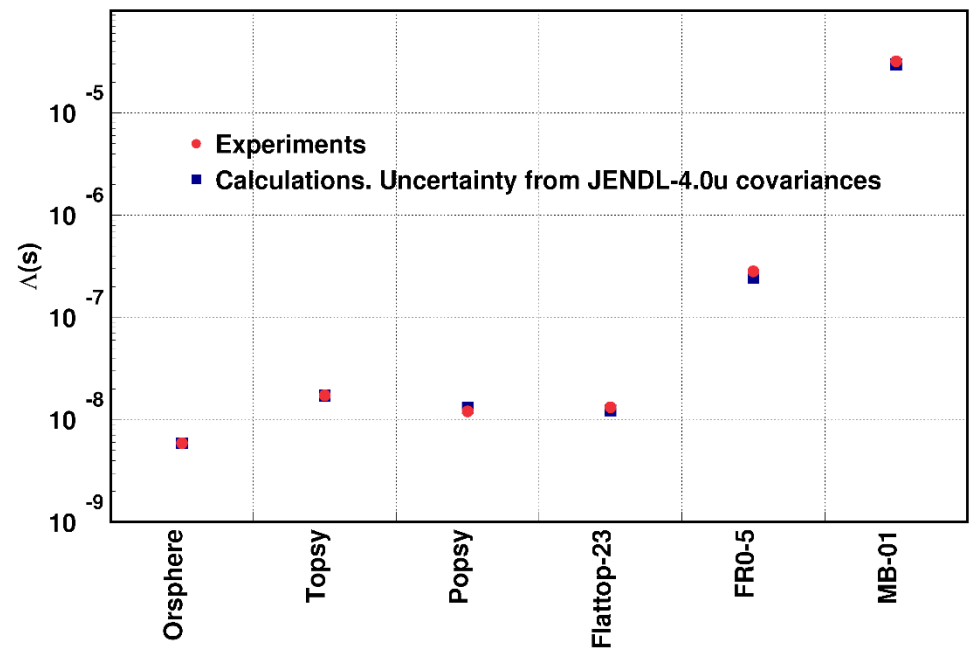
Reaction	$ISC = \sum_{\alpha} S_{\alpha} (\%/%)$
$^{235}\text{U}, \bar{\nu}_d$	0.9698 ± 0.0016
$^{235}\text{U}, (n, n)$	0.050 ± 0.014
$^{238}\text{U}, \bar{\nu}_d$	0.02035 ± 0.00003
$^{238}\text{U}, (n, f)$	0.00682 ± 0.00011
...	
$^{238}\text{U}, \bar{\nu}_p$	-0.01624 ± 0.00008
$^{235}\text{U}, (n, \gamma)$	-0.0458 ± 0.0009
$^{235}\text{U}, (n, f)$	-0.054 ± 0.012
$^{235}\text{U}, \bar{\nu}_p$	-0.966 ± 0.010



Validation results for Λ_{eff} (I)

- C/E differences larger than for β_{eff} (up to about 15%).
- Uncertainty due to nuclear data about 1-3%.
- While β_{eff} varies about 20% for a given fuel, Λ_{eff} varies over many order of magnitude (represent in logarithmic scale).
- C/E discrepancies likely due to inaccuracies in the amount of moderator rather than nuclear data.

Reaction	Λ_{eff} exp (s)	Λ_{eff} calc (s)
Orisphere	$(5.94 \pm 0.08) \times 10^{-9}$	$(5.91 \pm 0.18) \times 10^{-9}$
Topsy	$(1.74 \pm 0.03) \times 10^{-8}$	$(1.72 \pm 0.05) \times 10^{-8}$
Popsy	$(1.21 \pm 0.03) \times 10^{-8}$	$(1.31 \pm 0.04) \times 10^{-8}$
Flattop-23	$(1.33 \pm 0.05) \times 10^{-8}$	$(1.24 \pm 0.04) \times 10^{-8}$
Studsvik FR0-5	$(2.84 \pm 0.03) \times 10^{-7}$	$(2.46 \pm 0.04) \times 10^{-7}$
IPEN/MB-01	$(3.196 \pm 0.106) \times 10^{-5}$	$(2.9712 \pm 0.019) \times 10^{-5}$



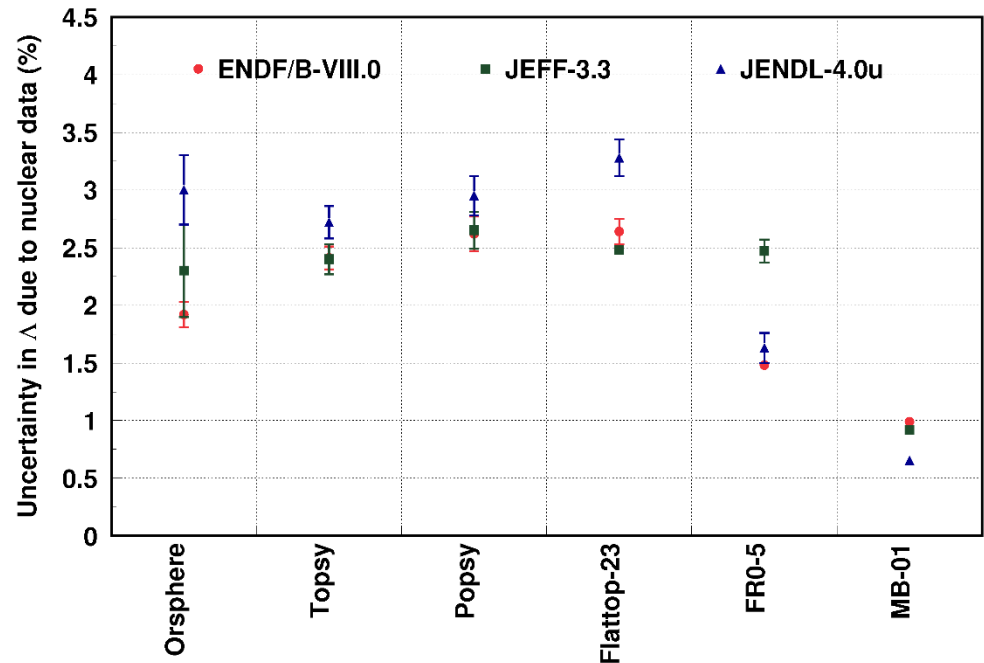
Validation results for Λ_{eff} (II)

Orsphere		Studsvik FR0-5		IPEN/MB-010	
Reaction	ISC (%/%)	Reaction	ISC (%/%)	Reaction	ISC (%/%)
$^{235}\text{U}, (n, n)$	0.26 ± 0.08	$^1\text{H}, (n, n)$	0.238 ± 0.005	$^{238}\text{U}, (n, \gamma)$	0.0718 ± 0.0005
$^{235}\text{U}, (n, n')$	0.20 ± 0.04	$^{238}\text{U}, (n, n')$	0.087 ± 0.003	$^{235}\text{U}, (n, \gamma)$	0.0333 ± 0.0003
$^{238}\text{U}, (n, n)$	0.012 ± 0.020	$^{63}\text{Cu}, (n, n)$	0.037 ± 0.007	$^{16}\text{O}, (n, \alpha)$	0.001705 ± 0.000024
$^{238}\text{U}, (n, n')$	0.011 ± 0.012	$^{65}\text{Cu}, (n, n)$	0.021 ± 0.005	$^{56}\text{Fe}, (n, \gamma)$	0.00170 ± 0.00018
...		
$^{235}\text{U}, (n, \gamma)$	-0.081 ± 0.005	$^{238}\text{U}, \bar{\nu}$	-0.2893 ± 0.0011	$^1\text{H}, (n, n)$	-0.272 ± 0.009
$^{235}\text{U}, \bar{\nu}_p$	-0.97 ± 0.06	$^{235}\text{U}, \bar{\nu}_p$	-0.704 ± 0.004	$^{235}\text{U}, (n, f)$	-0.8133 ± 0.0026
$^{235}\text{U}, \bar{\nu}$	-0.97 ± 0.06	$^{235}\text{U}, \bar{\nu}$	-0.707 ± 0.004	$^{235}\text{U}, \bar{\nu}_p$	-0.9085 ± 0.0022
$^{235}\text{U}, (n, f)$	-1.11 ± 0.07	$^{235}\text{U}, (n, f)$	-1.051 ± 0.004	$^{235}\text{U}, \bar{\nu}$	-0.9152 ± 0.0022

- Largest sensitivities due to nuclear data: fission related cross sections and scattering reactions in the moderator.

$$\Lambda_{eff} = \frac{\langle \phi^\dagger | \frac{1}{v} \psi \rangle}{\langle \phi^\dagger | \hat{F} \psi \rangle}$$

- Differences between libraries in uncertainty due to nuclear data smaller than in the case of β_{eff} .



Conclusions and acknowledgements

- Small number of benchmarks with kinetic information (β_{eff} , Λ_{eff}) in IRPhE → search in ICSBEP and scientific literature: 27 systems with experimental information for β_{eff} and 6 for Λ_{eff} .
- Very good C/E agreement for β_{eff} when uncertainties due to nuclear data in the calculations are taken into account.
- Large differences in the uncertainty due to nuclear data between libraries (covariance matrices for $\bar{\nu}_d$).
- C/E discrepancies for Λ_{eff} up to 15%, larger than uncertainty due to nuclear data, possibly due to the inaccuracies in the amount of moderator.
- Acknowledgements:
 - SANDA project (grant agreement 847552) of EU Horizon 2020 framework program.
 - ENRESA-CIEMAT agreement on “*Trasmutación de Radionucleidos de Vida Larga como soporte a la gestión de residuos radiactivos de alta actividad*”.
 - ICSBEP and IRPhE databases obtained through NEA Computer Program Services.
 - MCNP 6.2 code obtained through RSICC.