Evaluation of βeff measurements from BERENICE programme with TRIPOLI4® and uncertainties quantification.

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Abstract. The effective delayed neutron fraction (β_{eff}) is an important neutronic characteristic which deserves attention. The BERENICE measurements campaign which took place in the experimental facility MASURCA at CEA Cadarache was devoted to the experimental validation of the β_{eff} with the two cores R2 reference and R2 experimental using enriched uranium fuel and one core ZONA2 using MOX fuel. Given progresses in neutronic codes and nuclear data, it is important to have these experiments re-analysed with modern tools such as the Iterated Fission Probability method implemented in the Monte Carlo code TRIPOLI4® . This code gives credit to deterministic codes such as ERANOS for calculating β_{eff}. However, the asset of TRIPOLI4® is the possibility to get a better representation of experimental cores, especially the R2 experimental core which exhibit more experimental canals for hosting large fission chambers. It is also important for calculating parameters entering in the determination of the experimental values.

For JEFF3.2, the revised C/E ratios are of 1.2% ± 3.6% for the ZONA2 core and -1.2% ± 3.7 % for the R2 experimental core when using the Noise measurement technique.

The nuclear data uncertainty propagation has been leading to a 2.6% uncertainty for U-Pu core and 2.8% for enriched uranium cores with main contributors being the delayed neutron fission yield and the fission cross section of U238 values consistent with the Noise Technique re-analyses

Key Words: MASURCA, Beta-effectif, BERENICE, TRIPOLI4

1 Introduction to the BERENICE programme

The effective delayed neutron fraction (β_{eff}) is the limit of prompt criticality since for any reactivity lower than this value, the neutron chain reaction remains under control. That is why safety margins are dependent to this parameter and the core design is strongly affected by these margins. Hence, safety issues have motivated the experimental programme BERENICE, launched in January 1993 in the MASURCA facility, to improve the understanding of the effective delayed neutron fraction. The first two cores: R2 reference (a clean core) and R2 experimental (a core with large experimental axial channels (see **Fig. 1**)) used enriched uranium fuel and the last one was a Uranium-Plutonium fuel core: ZONA2 (see **Fig. 2**). Several experimental methods allow to get β_{eff}, two of these methods have been used in the course of this experimental programme: the ^{252}Cf method source and the noise method (see section **3.**). The new analysis of the experimental results is relevant considering the development of new techniques to get adjoint flux in Monte-Carlo code such as TRIPOLI4® and it allows a detailed representation of these cores (see section **2**). An evaluation of uncertainties on the effective delayed neutron fraction is also important, using ERANOS (a deterministic code) a sensitivity analysis to this neutronic parameter to nuclear data has been done and experimental uncertainties are presented in this paper (see section **4**).

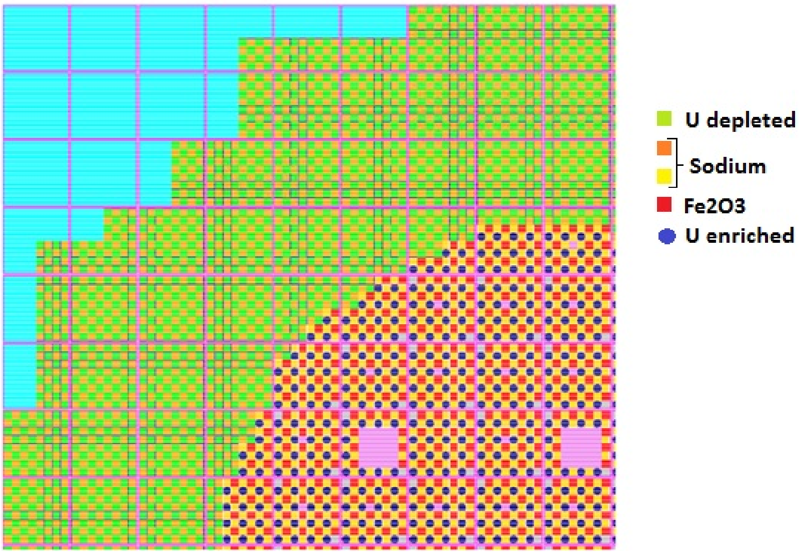

Figure 1: ¼ core of R2 exp

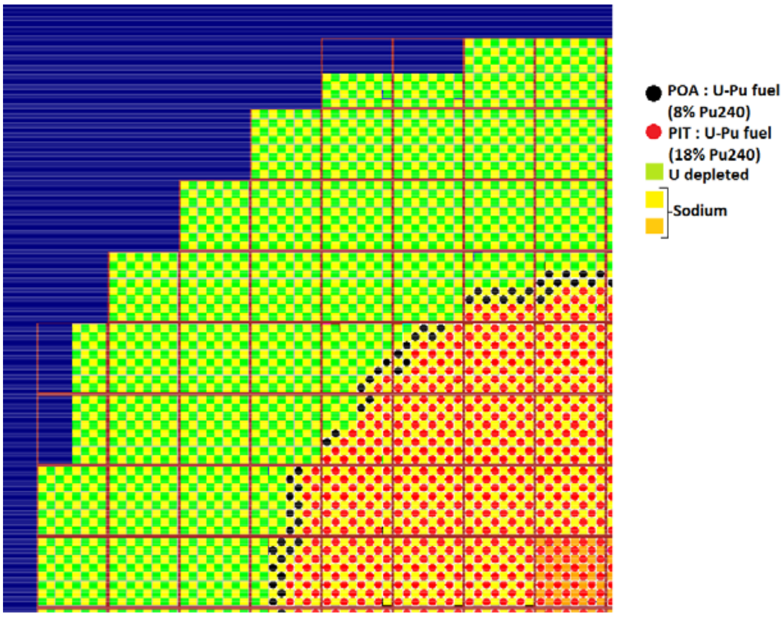

Figure 2: ¼ core of ZONA2

2 Numerical method for β_{eff} calculation

2.1 Deterministic method

The β_{eff} can be calculated with the perturbation theory [1] [2] from the Boltzmann forward and adjoint equations:

$$\left(\mathbf{A}-\frac{1}{k}\mathbf{F}\right)\Phi = 0 \text{ and } \left(\mathbf{A}^{+}-\frac{1}{k^{+}}\mathbf{F}^{+}\right)\Phi^{+} = 0 \qquad 2.1$$

with $\mathbf{A}$ the disappearance operator $\mathbf{F_d}$ and $\mathbf{F}$ the delayed and total production operator. The normalised reactivity effect only due to delayed neutron is:

$$\beta_{eff} = \frac{\langle\Phi^{+}|\mathbf{F_d}\Phi\rangle}{\langle\Phi^{+}|\mathbf{F}\Phi\rangle} \qquad 2.2$$

For each precursor p, the associated partial effective delayed neutron fraction is calculated as follows [3]:

$$\beta_{eff}^{p} = \frac{\iiint_r \left(\sum_g \chi_d \Phi_g^+\right)\left(\sum_g \nu_d \Sigma_{f,g} \Phi_g\right) d^3r}{\iiint_r \left(\sum_g \chi_{tot} \Phi_g^+\right)\left(\sum_g \nu_{tot} \Sigma_{f,g} \Phi_g\right) d^3r} \qquad 2.3$$

with: ν_d and ν_{tot} the delayed neutron yield of the precursor p and total fission neutron yield, χ_d and χ_{tot} the delayed neutrons fission spectrum of the precursor p and total neutron fission spectrum and $\Sigma_{f,g}$ the fission cross section. The total effective delayed neutron fraction is:

$$\beta_{eff} = \sum_p \beta_{eff}^{p} \qquad 2.4$$

In order to calculate the β_{eff} with the ERANOS procedure, delayed neutron fission spectra are given for the 8 precursor families with 33 energy groups. For each precursor p, the energy dependence of ν_d to the energy of the incident neutron is not taken into account in ERANOS.

2.2 Stochastic method with Tripoli4®

As seen for the deterministic method to calculate β_{eff}, the solution of the adjoint neutron transport equation is needed. For Monte-Carlo code this is much more difficult because of the continuous-energy treatment of nuclear data [4]. Consequently new methods were developed to get the importance of a neutron which is the adjoint flux definition. The Iterated Fission Probability method (IFP) is one of such method and was implemented in TRIPOLI4® [5]. That method defines the importance of the neutron placed in the core at a point $\vec{r}$ with an energy E by the number of fission this neutron will induced after L generations.

This method gives results for β_{eff} which are in good agreement with ERANOS as can be seen in the following table:

Table 2.1: Calculated β_{eff}

Calculated β_{eff} (pcm)				
Code	Nuclear Data	Cores : ZONA2	R2 reference	R2 experimental
ERANOS	JEFF-3.1	357,3	740,3	739,9
	JEFF-3.2	361,6	748,9	748,2
TRIPOLI4® (IFP)	JEFF-3.1.1	346.7 $\pm$ 0.9	736.1 $\pm$ 3.2	739.0 $\pm$ 1.9
	JEFF-3.2	349.9 $\pm$ 0.9	742.4 $\pm$ 3.2	748.4 $\pm$ 5.2

These results are obtained with ERANOS (JEFF-3.1 and JEFF-3.2 nuclear data) and with the IFP method TRIPOLI4® (4.10 version with JEFF-3.1.1 and JEFF-3.2 nuclear data). For TRIPOLI4® these associated uncertainties are the statistical uncertainties due to the Monte-Carlo method. Results between Monte Carlo calculations and deterministic ones differ from around 3% at the maximum (for ZONA2) and this is due to the approximations in the energy dependence of ν_d being used in ERANOS (see section **4**).

3 Experimental methods

Raw experimental measurements are not sufficient to derive β_{eff} because calculated terms are needed such as spectra importance or global fission rate. Therefore, the β_{eff} is split into a product of a measured part: P_m and a calculated part: P_c.

$$\beta_{\mathrm{eff}} = P_m . P_c \qquad 3.1$$

In this paper these notations will be used:

$$\langle f \rangle = \int_V d^3r \int_{4\pi} d^2\Omega \int_0^\infty dE\ f(\vec{r}, \vec{\Omega}, E) \qquad 3.2$$

$$\langle f \mid g \rangle = \int_V d^3r \int_{4\pi} d^2\Omega \int_0^\infty dE\ f\big(\vec{r}, \vec{\Omega}, E\big)\, g(\vec{r}, \vec{\Omega}, E) \qquad 3.3$$

3.1 The ^{252}Cf source method

The introduction in the core of a ^{252}Cf source creates a reactivity perturbation given by:

$$|\rho| = \beta_{\mathrm{eff}} |\rho_{\$}| = \frac{\langle S_{Cf} | \Phi^+ \rangle}{\langle \mathbf{F}\Phi | \Phi^+ \rangle} \qquad 3.4$$

This perturbation is measured by two fission chambers placed in the core. These measurements are combined with the parameter P_c defined as follow:

$$P_c = \frac{\varphi_{sc}}{K_c} \qquad 3.5$$

Where:

$\varphi_{sc} = \dfrac{\langle \chi_{Cf} \mid \Phi^+ \rangle}{\langle \chi_{U5} \mid \Phi^+ \rangle}$	The relative importance source of ^{252}Cf compared to the importance of the neutrons produced by the fission of U235 at the core center.
$K_c = \dfrac{\langle \chi_{fiss} \mid \Phi^+ \rangle \langle (\mathbf{F_p} + \mathbf{F_d}) \Phi \rangle}{\langle \Sigma_{f,U5} \Phi \rangle \langle \chi_{U5} \mid \Phi^+ \rangle}$	The calculated ratio of the total importance of production in the core compared to the importance of the fission of 1g of U235 at the core centre.

The parameters being evaluated with TRIPOLI4® are $\boldsymbol{\varphi_{sc}}$ and $\mathbf{K_c}$.

3.2 The noise method

The noise method considers that absorption and production of neutron in the core as random phenomena following a Poisson law. We can get to β_{eff} with signal processing by counting only the simultaneous events on two fission chambers and calculating the power spectral density [6]. This measured part is also combined with the P_c parameter given by:

$$P_c = {}^{2D}/_{K_c} \qquad 3.6$$

where:

$D = \dfrac{\overline{\nu(\nu - 1)}}{\bar{\nu}^2}$	The Diven factor takes into account the energetic dispersion of neutrons production. It is calculated with data from [7].
$K_c = \dfrac{\langle \Sigma_f \Phi \rangle}{\langle \Sigma_{f,U5} \Phi \rangle}$	The calculated ratio of the number of fission in the core compared to the number of fissions of 1g of U235 at the core centre.

The parameter being evaluated with TRIPOLI4® is K_c, the Diven factor is not calculated with TRIPOLI4® but with the deterministic code ERANOS. It is assumed that this approach brings a fairly good evaluation of the Diven factor.

3.3 Evaluation of P_c with TRIPOLI4®

3.3.1 The ^{252}Cf source method

The spectra importances, $\langle \chi \mid \Phi^+ \rangle$, and related responses are obtained with the Iterated Fission Probability [8] of TRIPOLI4® (the 4.9 version). Hence a new evaluation of the calculated parameter is possible. The TRIPOLI4® results are given in the following table and compared with the previous evaluation performed with ERANOS [9].

Table 3.1: Calculated parameter of the Cf252 method

Core	Code	φ_{sc}	K_c	P_c	β_{eff}
R2 réf	**ERANOS**	0.95743	0.46560	2.0564	791.16
	TRIPOLI4®	1.0165	0.53075	1.9153	739.83
R2 exp	**ERANOS**	0.97561	0.48310	2.0195	825.31
	TRIPOLI4®	1.0178	0.57126	1.7817	728.55
ZONA2	**ERANOS**	0.97901	0.42050	2.3282	358.36
	TRIPOLI4®	1.0604	0.50019	2.1200	326.45

With TRIPOLI4® the two parameters: φ_{sc} and K_c have a higher evaluated value than with ERANOS which result in a lower β_{eff} evaluation. The higher evaluation is explained by the fact that TRIPOLI4® allows a more accurate modelling of the core while ERANOS was using a RZ model with ERANOS and TRIPOLI4® also takes into account the energy dependence of delayed neutron production (as seen in **2.1**). Statistical uncertainties introduced by the use of Monte-Carlo method are, in this case, negligible.

3.3.2 Noise method

The noise method measurements were only conducted in R2 experimental and ZONA2 cores. Scores "fission" in TRIPOLI4® are used to compute the parameter: K_c.

Table 3.2: Calculated parameter of the Noise method

Core	Code	K_c	P_c	β_{eff}
R2 exp	**ERANOS**	0.31422	5.6414	767.55
	TRIPOLI4®	0.32275	5.4913	757.35
ZONA2	**ERANOS**	0.24033	7.3845	339.09
	TRIPOLI4®	0.23135	7.6710	345.61

With TRIPOLI4® the parameter: K_c has a larger value for R2 experimental core (enriched Uranium fuel) than ERANOS and TRIPOLI4® has a smaller value for ZONA2 core (U-Pu fuel) which result in different β_{eff} evaluations. Statistical uncertainties due to the use of Monte-Carlo method are, once again, negligible.

3.4 C/E results

A previous evaluation of P_c was performed with ERANOS in 2009 [9]. We expect that a comparison of the ratio C/E between ERANOS and TRIPOLI4® will highlight an improvement with the use of TRIPOLI4®.

Now the comparison between the calculated β_{eff} (see **2.2**) and the evaluation of "experimental" β_{eff} (using the evaluation of P_c see **3.3**) can be made. In the next table, the "experimental" β_{eff} obtained with ERANOS is compared to the calculated β_{eff} obtained with ERANOS (with JEFF3.1 and JEFF3.2) and the "experimental" β_{eff} obtained with TRIPOLI4® is compared to the calculated β_{eff} with TRIPOLI4® (with JEFF-3.1.1 and JEFF-3.2). The associated uncertainties (1σ) take into account: experimental uncertainties, uncertainties on nuclear data, statistical uncertainties (for TRIPOLI4®) and the bias ERANOS-TRIPOLI4® (for ERANOS).

Table 3.3: C/E results

C/E (Cf252 Method)								
Code		Cores						
	Nuclear Data	ZONA2		R2 reference		R2 experimental		
ERANOS	JEFF-3.1	0.9979	± 0.0592	0.9360	± 0.0480	0.8965	± 0.0495	
	JEFF-3.2	1.0090	± 0.0543	0.9466	± 0.0469	0.9066	± 0.0484	
TRIPOLI4	JEFF-3.1.1	1.0620	± 0.0505	0.9950	± 0.0441	1.0143	± 0.0458	
	JEFF-3.2	1.0720	± 0.0453	1.0035	± 0.0427	1.0272	± 0.0443	
C/E (Noise Method)								
Code		Cores						
	Nuclear Data	ZONA2		R2 reference		R2 experimental		
ERANOS	JEFF-3.1	1.0546	± 0.0524	-	-	0.9640	± 0.0432	
	JEFF-3.2	1.0664	± 0.0468	-	-	0.9748	±0.0417	
TRIPOLI4	JEFF-3.1.1	1.0032	± 0.0423	-	-	0.9757	± 0.0388	
	JEFF-3.2	1.0125	± 0.0359	-	-	0.9882	± 0.0372	

For the Cf252 method the ratio C/E is not improved by the use of TRIPOLI4® for ZONA2 core (further investigations on the importance of the ^{252}Cf source with TRIPOLI4® are needed) but for R2 cores it is greatly improved. However, for the noise method, this new evaluation improves the C/E ratio for both the ZONA2 and R2 experimental cores.

For JEFF3.2, the C/E ratios are 7.2% ± 4.5% for the ZONA2 core and 0.35% ± 4.3% for the R2 reference core when using the ^{252}Cf measurement technique and the C/E ratios are 1.2% ± 3.6% for the ZONA2 core and -1.2% ± 3.7 % for the R2 experimental core when using the Noise measurement technique.

4 Uncertainties

4.1 Experimental uncertainties

Each method have its own mean systematic uncertainties [10]. A series of measurements were conducted for each method so we have to take into account the dispersion of this series of measurements. The total experimental uncertainties are the quadratic sum of the method uncertainties and the dispersion. Results in the Table 4.1 show the dispersion of measurements are higher for R2 experiment because fewer measurements were conducted than in other cores (7 instead of 22):

Table 4.1: Experimental uncertainties

Method	Core	Method uncertainties (in %)	Dispersion of measurements (in %)	Total experimental uncertainties (in %)
Cf 252 source	R2 ref	3.4	0.20	3.41
	R2 exp	3.4	1.24	3.62
	ZONA2	3.5	0.52	3.54
Noise	R2 exp	2.3	1.40	2.69
	ZONA2	2.2	0.42	2.23

The noise method appears as the more accurate one and it can be expected to get information on nuclear data with these noise measurements. That is why a comparison with uncertainties due to nuclear data is needed.

4.2 Sensitivity and uncertainty analysis

Nuclear data such as cross sections or fission spectra are known within estimated uncertainties. That is why all neutronic parameters are affected by the nuclear data uncertainties. Deterministic codes allow to obtain sensitivities of neutronic parameters to each nuclear data and with these sensitivities (matrix S) and the covariance matrix associated to nuclear data, the final uncertainty on this parameter due to nuclear data is calculated with the sandwich formula:

$$\mathrm{I}^2 = \mathrm{SBS}^t \qquad 4.1$$

where: B the dispersion matrix which is based on the covariance matrix (such as COMAC developed at CEA [11]). The covariance matrix depends on the nuclear data library used: COMAC-Dev for JEFF-3.1 and COMAC-V1 for JEFF3.2.

Uncertainty results for R2 ref and R2 experimental cores are the same because neither the covariances nor the sensitivities are dependent on the geometry. The same uncertainty due to nuclear data on β_{eff} is hence obtained.

Table 4.2: Uncertainties on the β_{eff} in R2 cores

Isotope	Fission	Capture	Elastic	Inelastic	n.xn	Nu total	Nu delayed	Total Fission Spectrum	Total
JEFF-3.1	1.2609	0.7279	0.0807	0.2535	0.0071	0.1563	2.3874	0.3259	2.8093
JEFF-3.2	0.6064	0.5768	0.1118	0.3033	0.0448	0.1575	2.3843	0.3173	2.5724

Uncertainties results for ZONA2 core are given in the following table:

Table 4.3: Uncertainties on the β_{eff} in ZONA2 core

Isotope	Fission	Capture	Elastic	Inelastic	n.xn	Nu total	Nu delayed	Total Fission Spectrum	Total
JEFF-3.1	2.8060	0.4974	0.1562	0.8418	0.0162	0.3459	2.3113	0.3070	3.6046
JEFF-3.2	1.3816	0.1634	0.1622	0.7180	0.0866	0.3487	2.3070	0.3032	2.8226

Uncertainties due to nuclear data are reduced with JEFF-3.2 nuclear data thanks to the work conducted on U238 and Pu239 fission cross section (see in appendix A). However, these results show that a work to reduce uncertainties on ν_d data must be conducted. These uncertainties of 2.57% and 2.82% (with JEFF-3.2) have the same order of magnitude than the experimental ones.
In order to get information on nuclear data, it is hence needed to reduce the experimental uncertainties by use measurement techniques. An improved noise measurement is hence planned within the future experimental programme GENESIS of the refurbished zero power reactor (ZPR) MASURCA at CEA Cadarache.

5 Conclusion

The ASTRID project needs a better understanding on the uncertainties of the effective delayed neutron fraction because this parameter is the upper limit of the prompt criticality and sets the safety margins. The use of Monte-Carlo code TRIPOLI4® and its recent development of the Iterated Fission Probability method allow us to improve the C/E ratio and give credit to the deterministic code, ERANOS, for calculating β_{eff}. The detailed representation of cores and the use of an energy dependency of the delayed neutron emission to the incident neutron energy are the major contribution to this improvement. Also, the improvement comes from the calculated terms used to derive β_{eff} from raw experimental measurements. The C/E ratios are greatly improved when using the Noise measurement technique with 1.2% ± 3.6% for the ZONA2 core and -1.2% ± 3.7 % for the R2 experimental core.

The complementary use of the deterministic code ERANOS is fundamental for the uncertainty quantification process, with the sensitivity analysis and uncertainty propagation leading to a 2.82% uncertainty for U-Pu core and 2.57% for enriched uranium cores whose main contributors are the delayed neutron fission yield and the fission cross section of U238.

Only new experimental techniques (noise with faster electronic) as the ones envisaged within the future experimental programme: GENESIS in the recently refurbished facility: MASURCA could reduce current uncertainties of reference codes in calculating β_{eff}.

6 References

[1] A. Gandini, ‘A generalized perturbation method for bi-linear functionals of the real and adjoint neutron fluxes’, *J. Nucl. Energy*, vol. 21, no. 10, pp. 755–765, 1967.

[2] G. Rimpault *et al.*, ‘The ERANOS code and data system for fast reactor neutronic analyses’, presented at the PHYSOR 2002, Seoul, KOREA, 2002.

[3] C. Bouret, L. Buiron, and G. Rimpault, ‘Sensitivity and uncertainty analysis on reactor kinetic parameters using perturbation theory’, presented at the PHYSOR 2014, Kyoto, Japan, 2014.

[4] G. Rimpault, D. Blanchet, G. Truchet, J. Tommasi, and P. Dufay, ‘Uncertainty quantification of delayed neutron fraction of U235 based fuel cores’, presented at the PHYSOR 2016, Sun Valley, Idaho, USA, 2016.

[5] G. Truchet, P. Leconte, A. Santamarina, E. Brun, F. Damian, and A. Zoia, ‘Computing adjoint-weighted kinetics parameters in Tripoli-4® by the Iterated Fission Probability method’, *Ann. Nucl. Energy*, vol. 85, pp. 17–26, Nov. 2015.

[6] C. E. Cohn, ‘A simplified theory of pile noise’, *Nucl. Sci. Eng.*, vol. 7, no. 5, pp. 472–475, 1960.

[7] V. Zammit-Averlant, ‘Validation intégrale des estimations du paramètre Beta Effectif pour les réacteurs MOX et incinérateurs’, thèse, Aix-Marseille, 1998.

[8] G. Truchet, ‘Développements et validation de calculs à énergie continue pondérés par l’importance’, thèse, Université Grenoble Alpes, 2015.

[9] J. Tommasi, J. F. Lebrat, P. Archier, and J. M. Ruggieri, ‘Status of ERANOS-2 code system validation for sodium fast reactor applications’, presented at the PHYSOR 2010, Pittsburgh, Pennsylvania, USA, 2010.

[10] E. Fort, V. Zammit-Averlant, M. Salvatores, A. Filip, and J.-F. Lebrat, ‘Recommended values of the delayed neutron yield for: U-235; U-238 and Pu-239’, *Prog. Nucl. Energy*, vol. 41, no. 1–4, pp. 317–359, Jul. 2002.

[11] P. Archier, C. De Saint Jean, G. Noguere, O. Litaize, P. Leconte, and C. Bouret, ‘COMAC: Nuclear Data Covariance Matrices Library for Reactor Applications’, presented at the PHYSOR 2014- The Role of Reactor Physics toward a Sustainable Future, The Westin Miyako, Kyoto, Japan, 2014.

Appendix A

Uncertainties results for R2 cores:

Table A.1: Uncertainties on the β_{eff} with JEFF-3.1 nuclear data (and COMAC-Dev matrix) in R2 cores

Isotope	Fission	Capture	Elastic	Inelastic	n.xn	Nu total	Nu delayed	Total Fission Spectrum	Total
U235	0.1516	0.6531	0.0600	0.0392	0.0017	0.0721	2.2698	0.3089	2.3868
U238	1.2517	0.3170	0.0504	0.2583	0.0069	0.1721	0.7400	0.1039	1.4785
Na23	0.0000	0.0031	0.0214	0.0134	0.0001	0.0000	0.0000	0.0000	0.0254
Fe56	0.0000	0.0135	0.0563	0.0269	0.0000	0.0000	0.0000	0.0000	0.0639
O16	0.0000	0.0510	0.0425	0.0004	0.0000	0.0000	0.0000	0.0000	0.0664
Cr52	0.0000	0.0054	0.0029	0.0024	0.0000	0.0000	0.0000	0.0000	0.0066
TOTAL	1.2609	0.7279	0.0807	0.2535	0.0071	0.1563	2.3874	0.3259	2.8093

Table A.2: Uncertainties on the β_{eff} with JEFF-3.2 nuclear data (and COMAC-V1 matrix) in R2 cores

Isotope	Fission	Capture	Elastic	Inelastic	n.xn	Nu total	Nu delayed	Total Fission Spectrum	Total
U235	0.1538	0.5844	0.0544	0.0434	0.0031	0.0727	2.2642	0.3001	2.3625
U238	0.5865	0.1024	0.0635	0.2982	0.0447	0.1734	0.7474	0.1031	1.0138
Na23	0.0000	0.0027	0.0197	0.0173	0.0001	0.0000	0.0000	0.0000	0.0264
Fe56	0.0000	0.0121	0.0561	0.0297	0.0000	0.0000	0.0000	0.0000	0.0646
O16	0.0000	0.0381	0.0442	0.0004	0.0000	0.0000	0.0000	0.0000	0.0583
Cr52	0.0000	0.0052	0.0029	0.0031	0.0000	0.0000	0.0000	0.0000	0.0067
TOTAL	0.6064	0.5768	0.1118	0.3033	0.0448	0.1575	2.3843	0.3173	2.5724

Uncertainties results ZONA2 core:

Table A.3: Uncertainties on the $\boldsymbol{\beta_{eff}}$ with JEFF-3.1 nuclear data (and COMAC-Dev matrix) in ZONA2 core

Isotope	Fission	Capture	Elastic	Inelastic	n.xn	Nu total	Nu delayed	Total Fission Spectrum	Total
U235	0.0013	0.0019	0.0003	0.0008	0.0000	0.0018	0.0377	0.0046	0.0381
U238	2.6538	0.4860	0.0880	0.8504	0.0161	0.3456	1.5090	0.2022	3.0002
Pu238	0.0005	0.0003	0.0001	0.0001	0.0000	0.0022	0.0071	0.0007	0.0075
Pu239	0.9100	0.0796	0.0070	0.0942	0.0018	0.0121	1.7325	0.2169	1.9728
Pu240	0.0509	0.0093	0.0064	0.0236	0.0009	0.0048	0.2058	0.0769	0.2242
Pu241	0.0032	0.0039	0.0003	0.0039	0.0005	0.0016	0.1372	0.0196	0.1387
Pu242	0.0038	0.0006	0.0002	0.0012	0.0001	0.0026	0.0287	0.0026	0.0292
Na23	0.0000	0.0036	0.0451	0.0427	0.0001	0.0000	0.0000	0.0000	0.0620
Fe56	0.0000	0.0069	0.0533	0.0662	0.0000	0.0000	0.0000	0.0000	0.0852
O16	0.0000	0.0701	0.1085	0.0023	0.0000	0.0000	0.0000	0.0000	0.1292
Cr52	0.0000	0.0039	0.0035	0.0068	0.0000	0.0000	0.0000	0.0000	0.0086
TOTAL	2.8060	0.4974	0.1562	0.8418	0.0162	0.3459	2.3113	0.3070	3.6046

Table A.4: Uncertainties on the $\boldsymbol{\beta_{eff}}$ with JEFF-3.2 nuclear data (and COMAC-V1 matrix) in ZONA2 core

Isotope	Fission	Capture	Elastic	Inelastic	n.xn	Nu total	Nu delayed	Total Fission Spectrum	Total
U235	0.0013	0.0016	0.0003	0.0008	0.0000	0.0018	0.0379	0.0045	0.0383
U238	1.3243	0.1767	0.0948	0.7080	0.0865	0.3480	1.5263	0.2023	2.1753
Pu238	0.0005	0.0002	0.0001	0.0001	0.0000	0.0021	0.0070	0.0023	0.0077
Pu239	0.3913	0.0440	0.0135	0.0809	0.0018	0.0213	1.7111	0.2148	1.7709
Pu240	0.0443	0.0074	0.0054	0.0213	0.0008	0.0049	0.2086	0.0685	0.2230
Pu241	0.0033	0.0039	0.0003	0.0040	0.0005	0.0020	0.1367	0.0127	0.1375
Pu242	0.0038	0.0006	0.0002	0.0012	0.0001	0.0025	0.0285	0.0004	0.0289
Na23	0.0000	0.0050	0.0431	0.0577	0.0002	0.0000	0.0000	0.0000	0.0718
Fe56	0.0000	0.0065	0.0538	0.0693	0.0000	0.0000	0.0000	0.0000	0.0879
O16	0.0000	0.0509	0.1127	0.0024	0.0000	0.0000	0.0000	0.0000	0.1237
Cr52	0.0000	0.0037	0.0035	0.0084	0.0000	0.0000	0.0000	0.0000	0.0098
TOTAL	1.3816	0.1634	0.1622	0.7180	0.0866	0.3487	2.3070	0.3032	2.8226

Uncertainties due to nuclear data are reduced with JEFF-3.2 nuclear data thanks to a great work on U238 and Pu239 fission cross section. These results show that uncertainties on ν_d data must be improved.