Benchmarks on effective delayed neutron parameters and reactivity: a Brazilian IPEN/MB-01 contribution to the IRPhE project

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Abstract

The purpose of this work is to present the experimental results of the in-pile experiments performed at the IPEN/MB-01 Reactor for the determination of the effective delayed neutron parameters and reactivity. The methodologies employed were the macroscopic noise in the frequency domain, where the very low frequency range (< 1.0 Hz) was also exploited and analyzed, and the microscopic noise, which is based on the measurement of Rossi-α and Feynmann-α distributions at several subcritical levels. In this last case, a Two-Region Model was developed. The main advantage of these methodologies is to obtain the effective delayed neutron parameters in a purely experimental way, eliminating all parameters that are difficult to measure or calculate. Consequently, the uncertainties associated with these parameters are eliminated and the accuracy in the effective delayed neutron parameters is improved. Both techniques are claimed to be well defined and produce experimental data of very high quality. Finally, it is proposed to assign benchmark-values to β_{eff} (the effective delayed neutron fraction), to Λ (the prompt neutron generation time), to their ratio (β_{eff}/Λ) and also for the first time to the reactivity by means of the inhour equation. It is concluded that the experiments are acceptable benchmarks.

1. Introduction

It is well known the importance of delayed neutrons in the reactor physics field. The control and accident analysis of a nuclear reactor and the conversion of reactor period into reactivity, require the knowledge of the effective delayed neutron parameters as well as their decay constants. Even so, for the very important class of thermal reactor fueled with slightly enriched uranium, the experimental data concerning delayed neutrons parameters is scarce and in many cases its utilization is not so straightforward and well established.

Concerning thermal reactors fuelled with slightly enriched uranium, a literature survey shows that the available experiments related to β_{eff} and/or β_{eff}/Λ were performed only in the following facilities: Stacy, Winco, Sheba-II, Proteus, TCA, SHE-8, MISTRAL-1 and IPEN/MB-01. For the Stacy, Winco, Sheba-II and Proteus, the reported measured quantity is α, which is linked to β_{eff} at delayed critical through $\alpha_0 = \alpha(\rho=0) = \beta_{eff}/\Lambda$. The uncertainties in the α value measurements are 1.6%

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for Stacy, 0.03% for Winco, 1.8% for Sheba-II, and 0.6% for Proteus. Only the TCA, SHE-8, MISTRAL-1 and IPEN/MB-01 experiments, report measured values of β_{eff}, and their respective uncertainties are 2.2%, 4.6%, 1.6% and 0.9%. The number of experiments related to β_{eff} is thus quite small. In such a way, a collaborative effort to improve the β_{eff} measurements in thermal systems has been recommended.

In addition, current calculation/experiment discrepancies on measurements of the β_{eff}, for instance, are undesirable in design and operation of reactor control systems (D´Angelo, 2002). More precisely, a target accuracy of ±3%(1 s.d.) has been requested for the experimental β_{eff} (Sakurai et al., 1999). For β_{eff} calculations, the target accuracy which has been proposed is also ±3%(1 s.d.) (Rudstan, 2002; D´Angelo and Rowlands, 2002). Therefore, it is clear that more measurements are needed to provide the required degree of confidence in calculations. Indeed, it is by adjusting the delayed neutron yield to improve the agreement with measured values of β_{eff} that the most suitable data are obtained for inclusion in the nuclear data files.

In order to ensure accuracy, several different measurement techniques have been used in different facilities. Nowadays, the measured values of β_{eff} are not obtained directly but involve other parameters. The techniques used are Cf-source, macroscopic noise (spectral densities), microscopic noise (Rossi-α and Feynman-α), modified Bennet and Nelson number. The derivation of the β_{eff} value from all these techniques involves calculated parameters such as adjoint fluxes, spatial-correction factors, fission rates, etc. and/or results from other experiments, like reactivity, neutron source strength, detector efficiency, etc. Further, the Diven factor is common to all experiments, except the Cf-source technique, and introduces an uncertainty in measured β_{eff} values of about 1.3% (D´Angelo and Rowlands, 2002).

Concerning the determination of the reactivity of a particular reactor, it should be stressed here that this quantity is not measured, but it is a calculated quantity through the inhour equation. In general, the only measured variable used in this equation is the stable period, being the others variables (Λ, β_i and λ_i) obtained by calculational procedures. The uncertainties in these parameters are thus very difficult to be estimated so that the final reactivity calculation presents some lack of error propagation and its uncertainty is generally underestimated.

Based on these premises, the main purpose of this work is to fulfill the need of benchmark experiments for β_{eff}, β_{eff}/Λ, Λ and reactivity. For such a purpose, two categories of experimental procedures were employed: macroscopic noise and microscopic noise (Uhrig, 1970). In the macroscopic noise technique, the Cross Power Spectral Density (CPSD) and the Auto Power Spectral Density (APSD) are obtained and analyzed in a wide range of frequencies, from 5.82 mHz to 52 Hz (Diniz and Dos Santos, 2006). The experimental spectral densities are least-squares fitted assuming the point reactor model for the theoretical spectral densities derivation, and the parameters of the fit are β_i or λ_i. The β_i and λ_i parameters are used for reactivity calculations and the parameter β_{eff} is obtained as a by-product as $\beta_{eff} = \Sigma_i \beta_i$. In all cases it is assumed six groups of delayed neutrons.

The microscopic noise experiments rely on the measurements of the Rossi-α and Feynmann-α distributions at several subcritical levels (Kuramoto et al., 2007a, 2007b). The theoretical formulation is based on the Two-Region Model (Spriggs, 1997) which takes into account the core and the reflector of the reactor. The β_{eff}/Λ parameter is measured through the fitting of the Rossi-α and Feynmann-α distributions recorded at three different subcritical levels near the delayed critical state and extrapolating the fitted α vs. subcriticality to the critical condition. On the other hand, the β_{eff} parameter is obtained from the Rossi-α and Feynmann-α distributions recorded at very large subcritical levels. By fitting the curve Rossi-α and Feynmann-α vs. relative reactivity, the β_{eff} can be extracted directly and without the need of any data from theoretical calculations or other experiments. Finally, in the two-region model, the neutron lifetimes of the core and the reflector, τ_c and τ_r respectively, as well the neutron return fraction (from the reflector to the core) f can be obtained from the fitting procedure and the combination of these three quantities result in the prompt neutron generation time Λ of the whole system.

In the case of the reactivity, the β_i and λ_i parameters and the prompt neutron generation time Λ present in the inhour equation were all determined experimentally, thus making possible for the first time the calculation of the reactivity based solely on experimental parameters.

2. Overview of noise experiments

2.1. Macroscopic noise

The macroscopic noise experiment is based on the measurement of the spectral densities CPSD and APSD of the fluctuations of two gamma-compensated ionization chambers operating in current mode (CC-80 from Merlin Gerin) and placed symmetrically near the core (11.0 cm away from the most peripherical fuel rods). The frequency region of interest ranges from 5.82 mHz to 52 Hz, in order to include the delayed neutrons contribution, the plateau and the break frequency, $(\beta_{eff}/\Lambda)/2\pi$.

The experiment was performed with the reactor critical at a power level of 4.0 W and with its standard configuration of 28x26 rectangular array of UO_2 fuel rods. A very complete description of the IPEN/MB-01 reactor can be found in Dos Santos et al., (2004a). In the course of data acquisition, the control rods were "frozen" in order to avoid the interference of their movement in the low frequency region (< 1.0 Hz). In addition, the ventilation system and the water level pumping were turned off in order to have minimum electrical interference and minimum heat exchange with the external environment.

With an arrangement of two independent detectors, it was possible to get 1,000 averages of the CPSD between the two measurement channels and the APSD from each channel. These 1,000 averages were obtained through 104 partial averaged data sets, generally with a different number of averages for each one.

2.1.1 The least-squares approach and results

The least-squares-fitting approach considered in this work assumes only six groups of delayed neutrons. In all cases, the neutron generation time was fixed at 32 μs based on a series of measurements carried out previously (Dos Santos et al., 2004b). The theoretical expressions for the CPSD and the APSD used in the fitting to the experimental data can be found in (Diniz and Dos Santos, 2006 and Dos Santos et. al., 2008).

The procedure adopted in this work was to fix the decay constants λ_i (as given by the most important nuclear data libraries, namely ENDF/B-VI.8, ENDF/B-VI.8 (LANL review) and JENDL 3.3) and to fit the abundances β_i. This procedure is necessary in order to achieve convergence of the least-squares method, because with all the 12 parameters left free for fitting, the least-squares procedure does not converge. In addition, the β_1 parameter must also be kept fixed. This occurs due to the small number of experimental data points below the corresponding frequency of the λ_1 parameter, or ~ 0.012 Hz. However, since there is a linear constraint on β_1, *i.* e., $\beta_{eff} = \Sigma_i\ \beta_i$, there is no serious restriction on fixing it because of the gain of one degree of freedom.

In order to remove the systematic uncertainties due to the constant terms present in the spectral densities (reactor power, Diven factor, detector´s currents, gain of the amplifiers, etc.), these terms were grouped together in a single and allowed to be fitted. Next, these constant parameters were kept fixed in the course of the least-squares procedure for obtaining the abundances.

For the fitting procedure, error bars were considered for each point of the spectral densities. These error bars were obtained with the well-known standard deviation of the mean equation, since there are 104 partial averaged sets.

Table 1 shows the fitting results for the total effective abundances obtained as $\beta_{eff} = \Sigma_i\ \beta_i$ for the three libraries under consideration. As already mentioned, for each library the decay constants and the β_1 parameter were fixed in the course of the least-squares fitting. The uncertainty in β_{eff} was calculated through the error propagation of five quantities (β_2,… β_6), since β_1 was kept fixed.

Table 1
Effective abundances β_{eff} for the three libraries

ENDF/B-VI.8	ENDF/B-VI.8 [a]	JENDL 3.3
(7.47 ± 0.13)E-3	(7.51 ± 0.11)E-3	(7.47 ± 0.11)E-3

[a] LANL Revised by Young et. Al. (2003)

From Table 1 one can see that the results for β_{eff} are the same (taking into account the uncertainty of each) for the different decay constants of the three libraries. This is a remarkable result since the sum of the individuals β_i gives the correct value of β_{eff} and also shows that fixing β_1 during the least-squares procedure does not impose a serious restriction

For reactivity calculation, the parameters β_i and λ_i were obtained in a purely experimental way. In this case, however, the first decay constant came from an independent experiment carried out at the IPEN/MB-01 reactor. In such an experiment, using the Multiple Transient Technique (Dos Santos et al., 2006), the result for λ_1 was 0.012456 ± 0.000031 s^{-1}. Now, the least-squares procedure is iterative among the abundances and the decay constants separately, with just the λ_1 parameter kept fixed (Dos Santos, et al., 2008).

Table 2 shows the delayed neutron parameters β_i, λ_i and β_{eff} extracted in a fully experimental way, to be used in the reactivity calculation through the inhour equation. The reactivity in units of dollar for some positive and negative periods is shown in Table 3 (Λ was fixed at 32μs). The uncertainty in the reactivity calculation was estimated assuming that only β_i and λ_i (except λ_1) present errors, and that these parameters are uncorrelated, through the standard error propagation formula.

Table 2
Abundances and decay constants totally experimental

β_i	λ_i (s^{-1})
(2.679 ± 0.023)E-4	0.012456 (fixed)
(1.463 ± 0.069)E-3	0.0319 ± 0.0032
(1.34 ± 0.13)E-3	0.1085 ± 0.0054
(3.10 ± 0.10)E-3	0.3054 ± 0.0055
(8.31 ± 0.62)E-4	1.085 ± 0.044
(4.99 ± 0.27)E-4	3.14 ± 0.11
β_{eff} = (7.50 ± 0.19)E-3	

Table 3
Reactivity in $ for some periods and the set of totally experimental delayed neutron parameters of Table 2

T (s)	ρ ($)
1	0.776 ± 0.005
10	0.379 ± 0.007
100	0.092 ± 0.004
200	0.052 ± 0.002
-200	-0.076 ± 0.005
-100	-0.268 ± 0.014
-90	-0.437 ± 0.019
-85	-0.761 ± 0.025

2.2. *Microscopic noise*

The microscopic noise technique employs the very traditional Rossi-α and Feynman-α techniques but in this case, a two-region model (core and reflector) is employed to fit the final experimental data (Kuramoto et al., 2007a, 2007b).

Two different core configurations were considered for the microscopic noise experiments. The first core configuration was loaded in order to perform Rossi-α and Feynman-α measurements near the delayed critical condition to obtain β_{eff}/Λ. For this purpose, one small BF_3 neutron detector of 10mm diameter x 150mm height and sensitivity of 2.1 cps/nv was placed in the center of the active core (28x26 rectangular array of UO_2 fuel rods). In the second configuration, eight burnable poison rods were loaded in the core in order to reduce the excess reactivity of the core to nearly zero. Through this core configuration, when the control and safety rods were fully inserted, the subcritical reactivity was approximately -25000 pcm. Two detectors with different sensitivities were positioned in the reflector region to acquire the data. In such a way, Rossi-α and Feynman-α distributions could be recorded in a very large range of subcritical reactivity, nearly from -500 pcm to -25000 pcm, in order to obtain β_{eff}, Λ and other kinetic parameters in a purely experimental way.

2.2.1 *The β_{eff}/Λ measurement methodology*

In order to measure the ratio β_{eff}/Λ, time series data were recorded at three different subcritical levels (3.34, 4.77 and 5.73 pcm) near the delayed critical state. In total, three different measurements of the Rossi-α and the Feynman-α distributions were performed with the core system driven by its intrinsic source and different control rod positions. For both distributions, the theoretical development was based in the two-region model, but for small subcritical reactivities only one decay mode (one-region model) was experimentally observed.

Experimentally, relative changes in the subcritical reactivity ρ were estimated by the Neutron Source Multiplication Method (NSMM) (Misawa and Unesaki, 2003), where the inverse count rate of the BF_3 detector can be directly related to the subcritical reactivity.

The β_{eff}/Λ parameter is obtained by linear extrapolation of the fitting of the α values (at the three subcritical levels) versus the inverse count rate to the critical condition. It was considered error bars in these three values of α taking into account the variations of the detector count rate. In addition, the deviations in the independent variable (the inverse count rate) were transferred to the dependent variable through the standard error propagation.

Table 4 shows the results for the β_{eff}/Λ parameter.

Table 4
β_{eff}/Λ parameter from the two distributions

Rossi-α (s^{-1})	Feynman-α (s^{-1})
-235.28 ± 1.70	-235.57 ± 0.66

2.2.2 The β_{eff} measurement methodology

For the β_{eff} determination, the α values were measured in a very large range of subcritical reactivity (from -500 to -25000 pcm) using the Rossi-α and Feynmann-α methods in a two-region model, and the detectors placed in the reflector region. The hypothesis made in the Two-Region model was that the parameters τ_c, τ_r, f and β_{eff} were constants. Here, τ_c, and τ_r are the neutron lifetime of the core and reflector respectively, and f is the neutron return fraction from the reflector back to the core.

Through the fitting of the Rossi-α and Feynmann-α distributions to the α versus negative inverse count rate curve, the β_{eff} parameter, among others, can be extracted without the need of any data from theoretical calculations or other experiments. As in the previous section, error bars were considered in the fitting procedure, which take into account both contribution of α and the inverse count rate. Table 5 shows the several parameters obtained from the fitting employing the two-region model for the Rossi-α and Feynman-α distributions.

The comparison of the experimental results for β_{eff}/Λ in Tables 4 and 5 shows that the results are totally consistent, presenting very small deviation among them.

Table 5
Parameters obtained from the two distributions

	Rossi-α	Feynman-α
$\alpha_0 = \beta_{eff}/\Lambda$	$-234.75 \pm 2.34\ s^{-1}$	$-235.25 \pm 0.96\ s^{-1}$
τ_c	30.20 ± 1.02 μs	30.56 ± 0.48 μs
τ_r	0.243 ± 0.018 ms	0.232 ± 0.005 ms
f	0.0066 ± 0.0030	0.0055 ± 0.0012
β_{eff}	(7.54 ± 0.11)E-3	(7.50 ± 0.05)E-3

2.2.3 The Λ measurement methodology

The prompt neutron generation time Λ can be obtained by two different ways. Firstly, Λ can be trivially obtained by the relation

$$\Lambda = \beta_{eff} / (\beta_{eff}/\Lambda), \qquad (1)$$

where β_{eff}/Λ and β_{eff} values are given in Tables 4 and 5, respectively. Table 6 lists the results.

Table 6
Evaluation of Λ obtained from Eq. 1

	Rossi-α	Feynman-α
Λ (μs)	32.04 ± 0.52	31.84 ± 0.23

The second way is based in the fitted quantities τ_c, τ_r and f of Table 5 as (Spriggs et al., 1997):

$$\Lambda = [1/(1-f)]\ (\tau_c + f\tau_r) \qquad (2)$$

The final values are listed in Table 7.

Table 7
Evaluation of Λ obtained from Eq. 2

	Rossi-α	Feynman-α
Λ (μs)	32.03 ± 0.37	32.02 ± 0.22

Since Λ is derived from the fitted parameters τ_c, τ_r and f, its uncertainty is obtained using the well-known error propagation formula including the terms containing the off-diagonal elements of the covariance matrix.

Again, as can be seen from Tables 6 and 7, the results are totally consistent.

3. Recommended experimental data

As presented in the previous sections, three independent noise experiments were carried out in order to obtain the effective delayed neutron fraction, β_{eff}, the prompt neutron generation time, Λ, the ratio β_{eff}/Λ and reactivity by means of the inhour equation with the β_i and λ_i parameters totally experimental. Tables 8 and 9 summarizes the final results for β_{eff} and Λ, respectively

Table 8
Recommended experimental value for β_{eff}

Method	β_{eff} (pcm)
Rossi-α	754 ± 11
Feynman-α	750 ± 5
Spec. Density ENDF/B-VI.8	747 ± 13
Spec. Density ENDF/B-VI.8(LANL)	751 ± 11
Spec. Density JENDL 3.3	747 ± 11
Weighted mean	750 ± 4

Table 9
Recommended experimental value for Λ

Method	Λ (μs)
Rossi-α, Eq. 1	32.04 ± 0.52
Rossi-α, Eq. 2	32.03 ± 0.37
Feynman-α, Eq. 1	31.84 ± 0.23
Feynman-α, Eq. 2	32.02 ± 0.22
Spectral Densities	31.99 ± 0.33
Weighted mean	31.96 ± 0.13

In Tables 8 and 9, the weighted means were calculated with each value of β_{eff} and Λ weighted inversely by its own variance σ_i^2. The variance of the final weighted mean is thus given by $\sigma_\mu^2 = (1/\sigma_1^2 + \ldots + 1/\sigma_N^2)^{-1}$.

In Table 9, the value of Λ resulting from the Spectral Densities Method was obtained with other experimental data set and neglecting the delayed neutrons in the theoretical expression for the CPSD (Dos Santos et al., 2004b), and should not be confused with the Spectral Densities Method of section 2.1.1 where Λ was kept fixed at 32 μs in the course of the least-squares approach.

The recommended experimental values for β_{eff} and Λ given in Tables 8 and 9, respectively, were combined to yield the ratio $\alpha_0 = \beta_{eff}/\Lambda$. The final value is:

$$\boldsymbol{\beta_{eff}/\Lambda = 234.66 \pm 1.51\ s^{-1}}.$$

4. Recommended benchmark data

The benchmark-model for the kinetic parameters and their estimated uncertainties (1σ) are given in Table 10. The experimental β_{eff} and Λ values are given in Tables 8 and 9, respectively. Combining the geometric and material uncertainties (Dos Santos et al., IRPhE. 2008) and the experimental uncertainty from Tables 8 and 9, a total uncertainty can be readily obtained. Since the total uncertainty is small and well understood, the proposed experiment is acceptable as a benchmark experiment. Table 10 summarizes the Benchmark Model for β_{eff}, β_{eff}/Λ and Λ. The benchmark value for the reactivity is given in Table 3. The uncertainties considered there are the ones arising only from the experiments.

Table 10
Recommended benchmark values for β_{eff}, β_{eff}/Λ and Λ

β_{eff} (pcm)	β_{eff}/Λ (s^{-1})	Λ (μs)
750 ± 5	234.66 ± 7.92	31.96 ± 1.06

5. Theory/Experiment comparisons

The calculation analyses of the kinetic parameter experiments performed at the IPEN/MB-01 reactor were carried out employing the coupled NJOY/AMPX-II/TORT systems (Dos Santos et. al. 2000). The nuclear data libraries were prepared using NJOY 99.90 (MacFarlane and Muir, 2002). The thermal neutron scattering files S(α,β) needed for hydrogen bound in water were obtained with LEAPR module of NJOY The self-shielding treatment of the actinide resolved resonances in the neutron energy region from 0.625 eV to 5.53 keV was carried out by ROLAIDS and the neutron spectra in the several regions of the IPEN/MB-01 reactor by XSDRNPM which considers radial and axial slices of the IPEN/MB-01 reactor to get the final spectra for the broad group collapsing. The fine multigroup structure considered 620 groups (SAND-II structure). This set of fine multigroup were collapsed 16 broad groups with five groups in the thermal region (E<0.625eV.). The order of scattering (Legendre order expansion) was P_3 throughout the analyses. Subsequently, using the cross sections libraries generated before, TORT performed K_{eff} and forward and adjoint fluxes calculations considering a fully tri-dimensional geometric modelling of the IPEN/MB-01 reactor core.

The calculation of the effective kinetic parameters and reactivities were performed with the forward and adjoint fluxes calculated by the three dimensional S_n Code TORT. A special computer program was developed for the determination of the effective parameters with the forward and adjoint fluxes from TORT.

A comparison of β_{eff} and β_{eff}/Λ predicted by ENDF/B-VI.8, JEFF-3.1 and JENDL 3.3 with the experimental values, in terms of C/E, is shown in Table 11. This table shows clearly that, for the β_{eff} case, JENDL 3.3 library has the best performance. JEFF-3.1 is in an intermediate stage. Only JENDL3.3 attends the recommended accuracy for β_{eff} calculations (|C-E|/E less than 3%). In contrast, the same performance does not occur for its β_{eff}/Λ. However, this behavior is due mainly to the prompt neutron generation time (Λ). For JEFF-3.1, the deviations are relatively large for both β_{eff} and β_{eff}/Λ. The main reason for the β_{eff} discrepancy of these libraries is their higher values of the ^{235}U thermal yield. For the β_{eff}/Λ cases the reason for the discrepancies is due to both β_{eff} and Λ. The calculated prompt neutron generation time shows very little sensitivity to the nuclear data library employed. In a general sense when compared to the benchmark value (31.96 ± 1.06 μs) it shows a systematic underprediction of around 8%.

Table 11
Comparison in terms of C/E of the calculated β_{eff}, β_{eff}/Λ and Λ with the in-pile noise experiment

	ENDF/B-VI.8	JEFF 3.1	JENDL 3.3
β_{eff}	1.051	1.036	1.008
β_{eff}/Λ	1.141	1.116	1.094
Λ	0.928	0.929	0.922

The comparison of the reactivities given by the inhour equation (units of $) is shown in Table 12. According to Table 12, ENDF/B-VI.8 shows large deviations for negative periods in comparison to the results of JEFF3.1 and JENDL 3.3. It can be seen that there is a clear tendency to increase the deviation with the absolute value of the reactivity for negative periods. This occurs mainly due to the first decay constant adopted by ENDF/B-VI.8 which is overestimated relatively to the other two libraries. As mentioned, an independent measurement performed at the IPEN/MB-01 reactor also confirms that the first decay constant of ENDF/B-VI.8 is overestimated. For positive periods the deviations are smaller, but still significant, and show the tendency to decrease with larger reactivities.

Table 12
Comparison theory/experiment for the reactivities ($)

Period (s)	ENDF/B-VI-8	JEFF-3.1	JENDL 3.3
1	0.984	1.010	1.014
10	0.942	1.027	1.034
100	0.920	1.038	1.045
200	0.915	1.036	1.043
-200	0.911	1.035	1.040
-100	0.826	0.986	0.993
-90	0.718	0.954	0.966
-85	0.550	0.920	0.948

6. Conclusion

The experiments for the effective kinetic parameters and reactivities performed at the IPEN/MB-01 and their further evaluation to the IRPhE project have been successfully completed. The experimental approach employed did not require any quantity from calculation methodology or from another experiment. The data are of high quality and very valuable to check the current methodologies and nuclear data associated to these physical quantities. For the first time, a complete set of experimental effective delayed neutron parameters are measured and recommended to be used in the Inhour equation. The reactivity derived from the Inhour equation can be considered as benchmark values for this quantity. A comparison of β_{eff} and β_{eff}/Λ predicted by JEFF-3.1 and JENDL 3.3 with the experimental values, in terms of C/E, is shown in Table 11. This table shows clearly that, for the β_{eff} case, JENDL 3.3 library has the best performance. JEFF-3.1 is in an intermediate stage. Only JENDL3.3 attends the recommended accuracy for β_{eff} calculations (|C-E|/E less than 3%). In contrast, the same performance does not occur for its β_{eff}/Λ. However, this behavior is due mainly to the prompt neutron generation time (Λ). For JEFF-3.1, the deviations are relatively large for both β_{eff} and β_{eff}/Λ. The main reason for the β_{eff} discrepancy of these libraries is their higher values of the ^{235}U thermal yield. For the β_{eff}/Λ cases the reason for the discrepancies is due to both β_{eff} and Λ. The calculated prompt neutron generation time shows very little sensitivity to the nuclear data library used. In a general sense when compared to the benchmark value (31.96 ± 1.06 μs) it shows a systematic underprediction of around 8%.

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