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The Experimental Determination of the Effective Delayed Neutron Parameters: β_{eff}, β_{eff}/Λ and Λ of the IPEN/MB-01 Reactor

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A reactor noise approach has been successfully performed at the IPEN/MB-01 research reactor facility in order to determine experimentally the delayed neutron parameters β_{eff}, β_{eff}/Λ and Λ. In the measurement of the β_{eff} parameter, the reactor power, which is of fundamental importance, was obtained with a very high degree of accuracy by a fuel rod scanning technique and a subsequent irradiation of highly enriched ^{235}U foil for the fission density normalization. The final measured values of β_{eff}, β_{eff}/Λ show very good agreement with independent measurements. The theory/experiment comparison shows deviations as large as 6.8% for β_{eff} when the ENDF/B-VI.8 library and its revised version performed at LANL are employed. For the β_{eff}/Λ, these deviations are of the order of 15.6%. The best agreement is obtained for JENDL3.3 library, where it is found a deviation of only 1.9% in the C/E ratio of β_{eff}. This result fully supports the reduction of the ^{235}U thermal yield as proposed by Okajima and Sakurai. The C/E ratio of β_{eff}/Λ is relatively higher, 11.1%, but this is due to the underestimation of the calculated prompt neutron generation time, Λ.

KEYWORDS: Delayed Neutrons, Kinetic Parameters, Reactor Noise. β_{eff}, IPEN/MB-01

1. Introduction

Although comprising less than 1% of the neutrons emitted by fission, the delayed neutrons play a fundamental role in the reactor physics field. The control and accident analysis of a nuclear reactor and the conversion of reactor period into reactivity requires the knowledge of the effective delayed neutron parameters as well as their decay constants. In a nuclear reactor chain there are many fission products (approximately 250) which can be considered potential delayed neutron emitters. However, an experimental characterization of all these emitters is very difficult due to their very low yield and/or low half-lives as well as to their very complex transmutation chain. Yet, it is possible to measure their aggregate behavior and generate a few group model where the decay constants and abundances are mean values of various emitters with similar decay constant. Among the models utilized in the dynamic behavior of a nuclear reactor, the most common one is the point reactor model. A few number of precursor groups can be considered adequate for this model. To date practically all analysis are performed in a six-group model. The main effective delayed neutron parameters to be in such set of equations are β_{eff} (the effective delayed neutron fraction) and β_{eff}/Λ, where Λ is the prompt neutron generation time.

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There are several in-pile experimental approaches for the determination of β_{eff} [1] and β_{eff}/Λ [2,3]. This category of experiments is very important to the point reactor model because it can provide valuable information related to the effective delayed neutron parameters used in such a model. The available experimental support for the effective delayed neutron parameters is scarce and in may cases its utilization is no so straightforward and very well established. The main purpose of this work is an attempt to fulfill this need for a thermal reactor application. For such a goal, the experimental determination of β_{eff}, β_{eff}/Λ and the prompt neutron generation time (Λ) of the IPEN/MB-01 reactor will be presented. The IPEN/MB-01 research reactor facility consists of a 28x26 array of UO_2 fuel rods, 4.3% enriched and clad by stainless steel (type 304) inside of a light water tank. A complete description of the IPEN/MB-01 core can be found in Ref. 4. The theoretical analyses will consider the verification of the adequacy of the nuclear data of several libraries such as: ENDF/B-VI.8 [5], ENDF/B-VI.8 (LANL revision) [6], and JENDL-3.3 [7].

The importance of the measurements of β_{eff} is also present in the basic nuclear data libraries such as those used in this work. Indeed, it is by adjusting the yield to improve the agreement with measured values of β_{eff} that the most suitable data are obtained. Regarding the prompt neutron generation time besides of being a very important kinetic parameter, it pursuits a very important characteristic because from its own definition it is inversely proportional to $\nu\Sigma_f$ where in the case of the IPEN/MB-01 reactor, the ^{235}U fission cross section plays a major role. Consequently, Λ can provide valuable information related to the normalization of the ^{235}U fission cross section in the thermal neutron energy range.

2. Experimental Procedure for β_{eff} and β_{eff}/Λ

The experimental procedure [3,8,9] consists of obtaining the Cross Power Spectral Density (CPSD) from the signals of two compensated ionization chambers in the frequency range $\lambda_i << f << \beta_{eff}/\Lambda$ for the β_{eff} measurements and $f >> \lambda_i$ for the β_{eff}/Λ measurements, where λ_i is the decay constant of the ith group of delayed neutrons. The same set of data can be used for β_{eff} and β_{eff}/Λ measurements.

In this experiment the reactor was made critical in 4.0 W and 100 W as indicated by the control room instrumentation and the control rods were kept in the automatic control mode since their movement do not interfere in the frequency region of interest. Later, these power levels were corrected by the results of the fuel rod scanning technique. This technique which is more precise than the previous utilized during was specially developed to fulfill a need for a more accurate technique for the power normalization. The previous technique was based in a series of gold foils irradiation in the moderator and was developed to satisfy a need of the reactor commissioning. As will be shown, for the β_{eff} measurement, an accurate determination of the power of the reactor is very crucial. The ionization chambers were placed symmetrically in the west and east faces of the core, approximately 11 cm away from the fuel rods. In this way the detectors are located in the reflector region and about 8.0 cm away from the reflected thermal neutron peak.

The currents of the ionization chambers were then sent to a current-to-voltage converter (Keithley 614 electrometer) and next to a filter-amplifier which has a low frequency cut-off of 1.0 mHz. The resulting signals, composed only by the fluctuating components (amplified by a factor of 30), were then sent to a Dynamic Signal Analyzer which performs the CPSD.

Assuming the point kinetic model in the detectors position we can write the theoretical expression for the CPSD. For the β_{eff} measurement we have [9]:

$$\langle \Phi_{kl} \rangle = \frac{2 I_k I_l G_k G_l F_k F_l D g}{P b_{eff}^{2}} \quad (1)$$

and for the β_{eff}/Λ the CPSD has the form [9]

$$\Phi_{kl} = \frac{A}{(2pf)^2 + B^2} \quad (2)$$

where A is a constant and B is equal to β_{eff}/Λ.

In the equations (1) and (2) the *k* and *l* indexes refer to both measuring chains, I is the current from the ionization chambers, G is the gain of the filter-amplifier, F is the current to voltage factor, D is the Diven factor, γ is the energy released in fission and P is the reactor power. In both equations the delayed neutrons were disregarded.

From equation (1) one can get directly the β_{eff} where, in this case, $\langle\Phi_{kl}\rangle$ is the mean value of the CPSD in the plateau region (from 2 to 9 Hz approximately). On the other hand β_{eff}/Λ is obtained from equation (2) through a least-squares fit where A and B are the fitting parameters.

2.1. The Reactor Power Measurement

One of the key parameters in Eq. (1) is the reactor power [10]. This parameter was obtained by a twofold approach. Initially, a relative power density for every fuel rod was obtained by a fuel rod scanning equipment. Such device pursuits a HPGe detector which discriminates the gamma peak of ^{143}Ce. The counting in the photopeak of this fission product is proportional to the fission density. The scanning was performed in a twofold fashion. Initially, the active length of the fuel rod was passed continuously in the detector collimator. Such total counting of ^{143}Ce is again proportional to the fission density in the fuel rod. In the second matter, every other 1cm of fuel rod was counted in the HPGe detector such that an axial profile of the fission density normalized to the central point of the fuel rod could be obtained. This part was very important for the power normalization. The power normalization was performed through the irradiation of a highly enriched ^{235}U foil at the core center and subsequent determination of the absolute ^{143}Ce counting by means of a calibrated detection system. The conversion to fission density and specific power is made subsequently. The ^{238}U fission contribution and the correction factor for the foil perturbation are taken care by a calculational approach. The method has been found to be very accurate and relatively easy to perform. The power could be obtained with an uncertainty of 2.5%.

3. Uncertainty Analysis and Results

For the uncertainty estimate in the β_{eff} measurements, the following uncertainties were assumed (at 1 σ):

- 1.0% for the ionization chambers currents readings (from Keithley manual).
- 1.0% for the gain of the amplifiers (as measured in this work).
- 1.0% for the current to voltage factor (from Keithley manual).
- 3.0% for the Diven factor [10].
- 1.0% for the energy released per fission (estimated).
- 2.5% for the reactor power (as measured in this work).

The mean value ,$\langle\Phi_{kl}\rangle$, of the CPSD in the plateau region, can be obtained by averaging all points in this region and taking the standard deviation of the mean as the respective uncertainty. However, since the CPSD has intrinsic uncertainties (error bars in each frequency point) due to the measurement procedure, it seems better to obtain the mean value by a weighted least-squares fit of a constant. In this way the mean value will have an uncertainty given only by the fitting procedure. For each frequency bin, the error bar is given by [11]:

$$e\left(\Phi_{kl}\right) = \frac{1}{\sqrt{g_{kl}\ N}} \quad (\%) \qquad (3)$$

where g_{kl} is the measured coherence function and N is the number of averages.

Finally, the total uncertainty on β_{eff} is given by a standard error propagation through equation (1).

For the β_{eff}/Λ measurements, the uncertainty is obtained directly by a weighted least-squares fit of equation (2) where the weights are also given by equation (3).

Table 1 shows the results for β_{eff} and β_{eff}/Λ measurements at 100W and 4.0W. The power levels indicated are already corrected by the fuel rod scanning technique.

The final results for β_{eff} and β_{eff}/Λ can now be obtained through the arithmetic mean of the seven results of Table 1 and the standard error propagation, since these measurements can be considered as independent measurements. Also, the prompt neutron generation time, Λ, can be obtained by making $\Lambda = \beta_{eff} / (\beta_{eff}/\Lambda)$. These final results are shown in Table 2.

Table 1 - Results for β_{eff} and β_{eff}/Λ measurements at 100W and 4.0W corrected.

P (W)	**I_k (A)**	**I_l (A)**	**$\langle \Phi_{kl} \rangle$ (V^2/Hz)**	**β_{eff} (x 10^{-3})**	**β_{eff}/Λ (s^{-1})**
107.80[(a)]	11.20E-6	11,25E-6	(9.69±0.13)E-6	7.43±0.18	233.71±3.31
107.80[(b)]	11.20E-6	11,30E-6	(9.74±0.09)E-6	7.43±0.18	233.33±1.97
107.80[(c)]	11.21E-6	11.25E-6	(10.04±0.10)E-6	7.31±0.18	232.75±2.30
4.312[(d)]	456E-9	458E-9	(4.06±0.04)E-5	7.39±0.18	226.18±2.17
4.312[(e)]	458E-9	460E-9	(3.96±0.03)E-5	7.52±0.18	228.36±2.45
4.312[(f)]	456E-9	458E-9	(4.01±0.02)E-5	7.44±0.18	234.38±1.63
4.312[(g)]	457E-9	459E-9	(4.05±0.04)E-5	7.42±0.18	228.28±3.16

(a) 200 averages, span = 100 Hz and 800 lines of resolution (b) 340 averages, span = 100 Hz and 800 lines.
(c) 500 averages, span = 100 Hz and 400 lines of resolution (d) 300 averages, span = 100 Hz and 400 lines.
(e) 300 averages, span = 200 Hz and 800 lines of resolution (f) 500 averages, span = 100 Hz and 800 lines.
(g) 500 averages, span = 200 Hz and 400 lines of resolution.

Table 2 - Final experimental results for β_{eff}, β_{eff}/Λ and Λ.

β_{eff}	β_{eff}/Λ (s^{-1})	Λ (s)
(7.42 ± 0.07)E-3	231.00 ± 0.94	(32.12 ± 0.33)E-6

4. Independent Verification of the Measured Values.

Regarding the β_{eff}/Λ, Spriggs carried out a Rossi-Alpha experiment at IPEN in 1997 [2] with two miniatures BF^3 detectors located inside the active core (not in the reflector, as in the case of noise experiments here) and the measured result, β_{eff}/Λ = 232,9 s^{-1}, differs only 0.8% from the present noise result. This agreement supports the experimental results of this work and also shows that for this kind of measurements the presence of the detectors in the reflector has negligible effect on β_{eff}/Λ. More precisely, there is no evidence that spatial effects are important for the β_{eff}/Λ experiment performed at the IPEN/MB-01 reactor. Moreover, it should be noted here that the β_{eff}/Λ measurements through noise analysis do not depend on the magnitude of the CPSD but only on its shape, and thus, it seems to be a trustworthy measurement.

In the case of β_{eff}, the comparison is more restrictive since the independent verification is made with the results of a set of measurements also obtained through noise analysis and almost the same experimental conditions as in the present work. However, these measurements can be considered as independent ones. Firstly because the frequency range of data acquisition is not limited to the plateau region but it is from 0.005 to 50 Hz approximately in order to include the delayed neutrons contribution. Secondly, the functions to be fitted is the complete CPSD of which the Eq. (1) is a particular case when the delayed neutrons are disregarded. The fitting parameters are β_i or λ_i (i = 1...6) and β_{eff} can be obtained from $\beta_{eff} = \sum_{i=1}^{6} \beta_i$. It should be noted, however, that if the parameters to be fitted are β_i, then the decay constants, λ_i, must be fixed as well as the first abundance β_1, the fixed parameters coming from some known nuclear data library. This is a limitation of the method. The advantage of this method relies on the fact that it allows the determination of the effective beta without the need of the Diven factor and even the power normalization. The results shown a deviation of 1.6% when the decay constants are from ENDF/B-VI.8 (LANL review), 0.8% in the case of ENDF/B-VI.8 and 0.7% in the case of JENDL3.3 libraries relatively to the β_{eff} value of Table 2. It also should be stressed here that the spatial dependence of the β_{eff} measurements is less restrictive than that of the β_{eff}/Λ because of the lower frequency range of the former case Therefore, the conclusions reached here is that the present measurements of β_{eff} is completely supported by independent experiments and the final result can be considered accurate enough for the nuclear data validation.

5. Theoretical Determination of the Effective Parameters

The calculated effective delayed neutron parameters to be compared to the experimental values are defined following a standard mathematical approach [12]:

$$\beta_{eff_j} = \frac{1}{F}\int \ldots \int \chi_{d_j}(E)\,\beta_j \nu \Sigma_f(r,E')\,\phi(r,\Omega',E')\,\phi^*(r,\Omega,E)\,dr\,d\Omega'\,dE'\,d\Omega\,dE \quad (4)$$

$$\Lambda = \frac{1}{F}\iiint \frac{1}{v(E)}\,\phi^*(r,\Omega,E)\,\phi(r,\Omega,E)\,dr\,d\Omega\,dE \quad (5)$$

$$F = \int \ldots \int \chi(E)\,\nu \Sigma_f(r,E')\,\phi(r,\Omega',E')\,\phi^*(r,\Omega,E)\,dr\,d\Omega'\,dE'\,d\Omega\,dE\,, \quad (6)$$

where all the symbols follow the same meaning as in Ref. 12.

The effective delayed neutrons fraction is the sum of β_{effj} given by equation 4 for all j. The theoretical determination of the effective parameters does not have a benchmark capability such as those present in MCNP-4C [13] for the determination of k_{eff} and reaction rates of multiplying systems. Consequently, in the theory/experiment comparison the discrepancies of the calculated quantities will not be due solely to the nuclear data libraries used in the process but it will carry also the part due to the methodology itself. The approach adopted in this paper will be twofold. At IPEN, the commonly methodology used for reactor calculations and analyses is based on the couple systems HAMMER-TECHNION [14] for the cross section generation and weighting and CITATION [15] for the neutron diffusion in the reactor. This methodology will be used for the analysis of the experiments. In an attempt to make a methodology based on transport theory, this work will also employ the coupled NJOY/AMPX-II/TORT [16] systems. The advantage of this methodology as mentioned is the solution of the transport equation (forward and adjoint) as well as the flexibility to use several neutron groups. A specific computer program was written to perform the integrals shown in equations 4 through 6.

Initially, Table 3 compares β_{eff}, β_{eff}/Λ and Λ calculated by both methodologies for the ENDF/B-VI.8 case. The same trend was found for the other libraries. As shown in Table 3, the number of groups has an important bearing on β_{eff}. Considering the same number of groups, there is practically no difference between CITATION and TORT values of β_{eff}, and β_{eff}/Λ. The difference is really noticeable for the β_{eff} case when the number of groups is increased. Considering the prompt neutron generation time (Λ), the agreement between the methodologies is much better. There is no trend with S_N order or the number of groups. The 16-group structure used by TORT has 5 groups in the thermal energy region while the CITATION values consider just one. Therefore, the impact of the number of thermal groups in the determination of the prompt neutron generation time (Λ) is minimal.

Table 3 - Calculated results for β_{eff}, β_{eff}/Λ and Λ.

Effective Parameters	CITATION 4 groups	TORT		
		4 groups – S_2	4 groups – S_{16}	16 groups – S_{16}
β_{eff}	7.79853 x 10^{-3}	7.79991 x 10^{-3}	7.73787 x 10^{-3}	7.9241 x 10^{-3}
β_{eff}/Λ	262.31	261.93	265.18	267.05
Λ	29.7300 x 10^{-6}	29.7779 x 10^{-6}	29.17879 x 10^{-6}	29.6723 x 10^{-6}

Table 4 shows the results for β_{eff}, β_{eff}/Λ and Λ calculated by TORT for the nuclear data libraries considered in this work. Table 4 also shows the total ^{235}U thermal yields of these libraries. The TORT values were obtained using S_{16} and 16 groups. As shown in Table 4 the most stringent difference for the effective delayed neutron parameters β_{eff} and β_{eff}/Λ is given by JENDL3.3 which adopted a lower value of the ^{235}U thermal yield as proposed by Okajima and Sakurai [1]. In the case of the IPEN/MB-01 reactor most of the fissions (nearly 86%) come from the thermal neutron energy region where ^{235}U plays a major role. Consequently the results expressed in Table 4 is mainly the ^{235}U effect. The prompt neutron generation time (Λ) as shown in Table 4 has very little sensitive to the nuclear data library used in the analysis. Therefore, the differences found in the β_{eff}/Λ is mainly due to β_{eff}.

Table 4 - Final calculated results for β_{eff}, β_{eff}/Λ and Λ given by TORT(S_{16} and 16 groups).

b$_{eff}$			**b**$_{eff}$/**L**		
ENDF/B-VI.8	ENDF/B-VI.8$^{(a)}$	JENDL 3.3	ENDF/B-VI.8	ENDF/B-VI.8$^{(a)}$	JENDL 3.3
7.9241 x 10^{-3}	7.9238 x 10^{-3}	7.5616 x 10^{-3}	267.05	267.04	256.60
L			**^{235}U Thermal yield**		
ENDF/B-VI.8	ENDF/B-VI.8$^{(a)}$	JENDL 3.3	ENDF/B-VI.8	ENDF/B-VI.8$^{(a)}$	JENDL 3.3
2.9672 x 10^{-5}	2.9672 x 10^{-5}	2.9468 x 10^{-5}	1.670 x 10^{-2}	1.670 x 10^{-2}	1.585 x 10^{-2}

(a) LANL review

6. Theory/Experiment Comparison

A comparison of β_{eff} and β_{eff}/Λ predicted by ENDF/B-VI.8, ENDF/B-VI.8(LANL Review) and JENDL 3.3 with the experimental values is shown in Table 5. From Table 5 it can be seen that for the β_{eff} case JENDL 3.3 library shows the best performance. As stated , the lower value of β_{eff} of JENDL3.3 is due mainly to the lower value of the ^{235}U thermal yield.

Therefore a reduction of this quantity as proposed by Okajima and Sakurai is completely supported by the experimental work of this paper. In contrast, the same does not occur for β_{eff}/Λ. For the ENDF/B-VI.8 libraries and even for its revised version performed at LANL, the deviations are relatively high for both β_{eff} and β_{eff}/Λ measurements. The main reason for the β_{eff} discrepancy of these libraries are their high values of the ^{235}U thermal yield. For the β_{eff}/Λ case the reason for the discrepancies are both due to β_{eff} and to Λ which will be discussed shortly. In the JENDL3.3 this discrepancy is due mainly to the prompt neutron generation time.

Table 5 - Comparison of the calculated β_{eff} and $\beta_{eff}/\Lambda$with the in-pile noise experiment.

$\mathbf{b}_{eff}$ (C/E)			$\mathbf{b}_{eff}/\mathbf{L}$ (C/E)		
ENDF/B-VI.8	ENDF/B-VI.8[(a)]	JENDL 3.3	ENDF/B-VI.8	ENDF/B-VI.8[(a)]	JENDL 3.3
1.068	1.068	1.019	1.156	1.156	1.111

(a) LANL review.

As mentioned, the calculated prompt neutron generation time shows very little sensitivity to the methodology employed as well as to the nuclear data library used. In a general sense when compared to the experimental value ($32.12 \pm 0.33\mu s$) it shows a systematic underprediction of about 7.4%. This is quite a surprising result since the prompt neutron generation time is a well defined quantity. This comparison leaves the impression that the calculation of Λ has to be performed in a different way from the traditional multigroup method. Analyzing equations (4) and (5), one may not that the parameter F is common in both equations. Since as shown in the analysis, the discrepancy found in β_{eff} is mainly a nuclear data problem related to the ^{235}U thermal yield, it may be conclude that the parameter F is nearly correct in both equations. Therefore, the source of the discrepancy of Λ may be attributed to the numerator of equation (5). The 1/v cross section used in equation (5) was obtained with the neutron flux as a weighting function. However in order to preserve equation (5) in a multigroup model, the cross section 1/v should be weighted by the product of the forward and adjoint fluxes. Since the implementation of such approach is quite laborious in the computer code XSDRNPM, this aspect will be left as a suggestion for a future work.

7. Conclusions

The experimental determination of β_{eff} and β_{eff}/Λ of the IPEN/MB-01 reactor employing a reactor noise method has been successfully accomplished. The experimental results are in a very good agreement with the results of independent measurements The experimental uncertainties are small enough so that the reactor noise method can be considered a good technique for this kind of measurements. The results obtained in this work support the reduction of the ^{235}U thermal yield in order to have a better agreement between theory and experiment. This aspect is clearly seen in the performance of JENDL3.3 which has a lower value for the thermal yield of ^{235}U. In contrast, ENDF/B-VI.8 and its revised version performed at LANL overpredict β_{eff} by as much as 6.5%. β_{eff}/Λ shows a high deviation for all libraries analyzed in this work. The main reason of that is the underprediction of the calculated prompt neutron generation time. This quantity shows a systematic underprediction of around 7.4%. The suggestions of this work are the incorporation of a lower ^{235}U thermal yield in the future versions of the ENDF/B-VI releases in order to have a better agreement of β_{eff} with experiments and also to weight the 1/v cross section with the product of the forward and adjoint fluxes.

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