A Noise Analysis Approach for Measuring Effective Delayed Neutron Parameters in the IPEN/MB-01 Reactor

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Abstract. A reactor noise approach has been successfully performed at the IPEN/MB-01 research reactor facility in order to determine experimentally the effective delayed neutron parameters β_i and λ_i in a six-group model and the point kinetic equations. The theory/experiment comparison shows that for the abundances the JENDL3.3 presents the best performance while for the decay constants the revised version of ENDF/B-VI.8 shows the best agreement. As a by-product and a consistency check, the β_{eff} parameter was obtained without the need of the Diven factor and the power normalization and it is in excellent agreement with independent measurements. Also, the β_{eff} result is independent on the nuclear data library used in the fitting procedure. The reflector effect appears to be important only for frequencies larger than β_{eff}/Λ, and the results for the kinetic parameters are almost the same as for the non-reflected case.

INTRODUCTION

Since the first stages of study on the controlled nuclear chain reaction, the fundamental role of the delayed neutrons became evident and a worldwide effort, both experimental and theoretical, has been made until now [1] in order to establish a consistent set of delayed-neutron kinetic parameters. The control and accident analysis of a nuclear reactor as well as the conversion of period into reactivity requires the knowledge of the abundances (β_i) and the decay constants (λ_i) of the delayed neutrons.

There are several experimental ways to determine these delayed-neutron parameters [2] and they are generally classified as "in-pile" and "out-of-pile" experiments. The results of an out-of-pile experiment constitute the basic nuclear data from which the system-applicable or effective parameters can be obtained, for a specific reactor, through specialized codes such as CITATION [3] or TORT [4]. On the other hand, the in-pile experiments give results relative to the core as a whole and the parameters obtained are called effective parameters.

The purpose here is to introduce a new in-pile experiment based on the measurement of the fluctuations of the neutron population [5]. In this technique the Cross Power Spectral Density (CPSD) between the signals of two neutron detectors and also the Auto Power Spectral Densities (APSD) are measured in a very low-frequency range and the result is least-squares fitted assuming a point-kinetic model. The parameters of the fit are β_i or λ_i. The theory/experiment comparison will be made with three nuclear data libraries, namely ENDF/B-VI-8, its revised version at LANL, and JENDL3.3.

EXPERIMENTAL PROCEDURE

The IPEN/MB-01 reactor [6] was made critical at a power level of 4.0 W with the control rods "frozen" in order to avoid the interference of its movement in the very low-frequency region (< 1.0 Hz). Two boron-lined compensated ionization chambers, operating in current mode, were used to obtain the DC mean currents that are proportional to the local neutron flux. The ionization chambers were placed symmetrically on one of the symmetry axes of the nucleus, 11 cm away from the first fuel rods and 8 cm away from the reflector neutron peak as shown in Fig. 1.

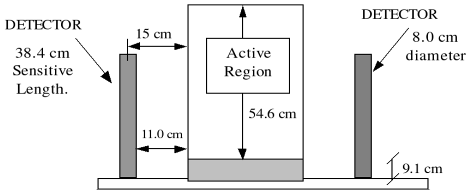

FIGURE 1. Side view of the nucleus and the detector positioning.

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These currents are converted into voltage signals by two electrometers, and the DC part is removed by two filter-amplifiers developed at IPEN. The AC or fluctuating part of the voltage signals are amplified by a factor of 30 and then sent to the dynamic signal analyzer (DSA) where the spectral densities are obtained.

The data acquisition by the DSA was made in two-frequency intervals with different resolutions for each one in order to get the spectral densities including the plateau and beyond. These intervals were 0-3.125 Hz (1600 lines of resolution) and 2-52 Hz (800 lines). One thousand averages were obtained of the spectral densities and the coherence function.

Considering six groups of delayed neutrons and the point reactor model, the theoretical APSD and the CPSD, which will be used for the fitting procedure, are given, respectively, by [6]:

$$\Phi_{xx}(f) = |G(f)|^2 A + B \tag{1}$$

and

$$\Phi_{xy}(f) = |G(f)|^2 C \tag{2}$$

where:

$$G(f) = \frac{\Lambda}{i\omega\Lambda + \sum_{j=1}^{6} \frac{i\omega\beta_j}{i\omega+\lambda_j}} \tag{3}$$

is the zero-power point-reactor transfer function and A, B, and C are constants that depend upon chamber currents, reactor power, the Diven factor, and other constants due to the electronic equipment. These constant terms will be left free for adjusting in the fitting procedure. The only frequency-dependent term is given by $G(f)$. In Eq. (1) the B term is the non-correlated noise due to the random detection process.

In Eqs. (1) and (2) the noise-equivalent source was obtained by the standard Schottky formula [7] with no inclusion of reflector effects nor delayed neutrons. This later contribution is so small that it can be neglected [8, 9]; the reflector effects will be included later, and the results will be compared. Also, it is assumed that there is no spatial dependence (at least in the frequency range of interest), which is a good assumption since the reactor is small and the detectors are large and positioned symmetrically with one another [8, 9].

RESULTS

The comparison theory/experiment for the ENDF/B-VI.8, its revised version at LANL, and JENDL3.3 libraries are shown in Table 1 where the final experimental results for the parameters were obtained as the arithmetic mean of the fitting results of the two APSDs and one CPSD since they can be considered as independent measurements. For the fitting procedure, the parameters β_1 and λ_1 must be kept fixed in order to achieve convergence and, in order to make the theory/experiment comparison feasible, the abundances are obtained with the decay constants fixed and vice-versa. The effective delayed neutron fraction will be obtained as a sum of the partial β_is. Rigorously speaking, this procedure will carry some library dependence on β_{eff}. However, it is demonstrated that this dependence is minimal. In all cases, Λ was fixed at 32μs based on a series of measurements carried out previously [10]. Error bars in each frequency point of the spectral densities were included as the standard deviation of the mean.

TABLE 1. C/E ratios for the three libraries.

ENDF/B-VI.8		**LANL rev**		**JENDL3.3**	
β_i	λ_i	β_i	λ_i	β_i	λ_i
1.000	1.000	1.000	1.000	1.000	1.000
0.910	1.129	1.157	0.998	1.067	0.890
0.926	1.252	0.764	1.009	1.116	0.886
1.093	1.116	1.137	1.091	0.939	0.935
1.435	1.021	0.972	1.062	1.126	0.886
0.876	0.701	1.428	1.086	0.680	0.783
β_{eff} C/E=1.044		β_{eff} C/E=1.039		β_{eff} C/E=1.000	

It should be stressed here that the β_{eff} parameter was obtained without the need of the Diven factor and power normalization and that the results are independent of the nuclear data library used for the fitting procedure. In fact, for the ENDF/B-VI.8 β_{eff} = (7.4707±0.0571) $\times 10^{-3}$, for its revised version at LANL β_{eff} = (7.5066±0.0471) $\times 10^{-3}$, and for JENDL3.3 β_{eff} = (7.5066±0.0480) $\times 10^{-3}$.

One of the most important applications of the kinetic parameters is the relation between reactivity and the asymptotic period of a nuclear plant. The inhour equation gives this relation. Table 2 shows the C/E ratio for the reactivities, calculated in units of $, for the three libraries under consideration. In all cases the prompt-neutron generation time was fixed at 32 μs.

It should be mentioned that even the theoretical results for the reactivity show discrepancy among the libraries. The ENDF/B-VI.8 shows large deviations for negative periods in comparison with the results of its revised version at LANL and at JENDL 3.3. 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. An independent measurement performed at the IPEN/MB-01 reactor [11] 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 a tendency to decrease with larger reactivities.

TABLE 2. Comparison theory/experiment for reactivity calculations.

Period (s)	ENDF/B-VI.8	LANL review	JENDL3.3
1	0.976	0.973	1.034
10	0.890	0.959	1.081
100	0.838	0.983	1.124
200	0.834	0.985	1.129
-200	0.827	0.991	1.133
-100	0.844	0.985	1.100
-90	0.860	0.979	1.072
-85	0.875	0.973	1.044

The comparison theory/experiment shows clearly that for the two versions of the ENDF/B-VI.8 library the reactivity obtained with theoretical parameters is always underestimated, while for JENDL 3.3 the contrary occurs. The major global deviation is due to the ENDF/B-VI.8 library, which shows a C/E ratio of 17% for some reactivities, both positive and negative. The best performance is due to its version revised at LANL that shows a maximum deviation of only 4.1%. The JENDL 3.3 library also shows high deviations and a tendency to increase the deviation with lower reactivities.

In order to include the reflector effect, Cohn's model [12] for reflected reactor kinetics seems to be a good starting point. Since in this experiment the detectors were placed in the reflector, it the corresponding equations must be used. In the case of the CPSD of the reflector, the expression used is Eq. (13) or (22) of [12] multiplied by constant terms due to the electronic equipments and the normalization factor [13] $(Lc/LrKcr)^2$, which takes into account the neutron population in the core and reflector via the probability of leakage of neutrons from the core to the reflector, Kcr. Lc and Lr are the neutron lifetimes in the core and reflector, respectively.

It should be noted that Cohn´s model introduces two neutron lifetimes, Lc and Lr, and a third (global) L, which is related to the other two through $L = [Lc + Lr(1 - Kco)]/Kco$, where Kco is related to the multiplication factor of the core, but they have no relation to the well-known parameter Λ. Thus, in this model, the physically meaningful parameter β_{eff}/Λ is not present explicitly, although it can be recovered through a least-squares procedure of the experimental data and searching for the 3dB cutoff of the adjusted spectral densities.

In order to compare the results for the abundances of both models (non-reflected and reflected), a least-squares procedure was performed using the same preceding data set for the CPSD, except without error bars and the initial parameters of the JENDL3.3 library. For the reflected case, L, Lc, and Lr, as well as Kco and Kcr, must be supplied. These parameters were initially estimated considering that the β_{eff}/Λ parameter must be preserved. Next, they were left free for adjustment together with the abundances. The decay constants were kept fixed. Finally, an iterative procedure was used between the abundances and Cohn's parameters until variations in all parameters were no longer observed. For the Cohn's parameters it was obtained: $L = 2,75885 \times 10^{-4}$ s, $Lc = 2,11446 \times 10^{-5}$ s, $Lr = 1.41512 \times 10^{-3}$ s, $Kco = 0.994$, and $Kcr = 0.319$. Since the error in the fitting parameters is larger as more parameters are left free for adjusting, all the parameters of the Cohn's model were kept fixed for the final fitting of the abundances. Note that the expression for L does not agree very well with the above values for L, Lc, and Lr. The results for the abundances using the two models and JENDL3.3 library are shown in Table 3. The β_1 parameter was kept fixed in both cases.

As can be seen, the results for the abundances for the non-reflected and reflected models are almost the same. For the decay constants the results have a similar behavior, also showing a very small difference for the two models. In this case, the three lifetimes, Kco, and Kcr were obtained through an iterative procedure with the decay constants and the results had no expressive difference in comparison with the case where the abundances were used. Thus, it can be concluded here that the reflector effect is not important for the present case, since only low frequencies are involved. The fitting results are very dependent on the lifetimes L, Lc, and Lr, and to a lesser extent on Kco and Kcr. Although the meaning of these lifetimes are not totally clear, they were obtained through a least-squares fitting of real data, where the fitting parameters were the lifetimes and the abundances or the decay constants for the three libraries. The results for the lifetimes were almost the same for all libraries.

CONCLUSIONS

The results of this work show that reactor noise analysis can be employed in the very low-frequency range where the delayed-neutron contribution is dominant. The experimental procedure did not require any sort of correction factor and the least-squares procedure adopted allowed that the fitted parameters did not depend on the electronic

TABLE 3. Results for the abundances in the non-reflected and reflected reactor models.

Non-Reflected	Reflected
2.66614×10^{-4}	2.66614×10^{-4}
$(1.4376 \pm 0.0140) \times 10^{-3}$	$(1.4581 \pm 0.0125) \times 10^{-3}$
$(1.4098 \pm 0.0321) \times 10^{-3}$	$(1.4236 \pm 0.0304) \times 10^{-3}$
$(3.0433 \pm 0.0490) \times 10^{-3}$	$(3.0656 \pm 0.0456) \times 10^{-3}$
$(8.7105 \pm 0.4526) \times 10^{-4}$	$(8.6540 \pm 0.4303) \times 10^{-4}$
$(4.7829 \pm 0.2815) \times 10^{-4}$	$(4.8677 \pm 0.2647) \times 10^{-4}$
$\beta_{eff} = (7.5067 \pm 0.0414) \times 10^{-3}$	$\beta_{eff} = 7.5661 \pm 0.0391) \times 10^{-3}$

equipment uncertainties nor on the constants present in the spectral densities. In this way, the fitted parameters did not depend on the magnitude of the spectral densities but only on their shapes. The theory/experiment comparison has shown that there are two libraries with good performance: JENDL 3.3 in the case of the abundances and ENDF/B-VI.8 (LANL review) in the case of the decay constants. The current version of ENDF/B-VI, namely release 8, presented the worst performance for all cases, probably due to the high value of its first decay constant, 0.0133 s^{-1}, in comparison with the value around 0.0124 s^{-1} for the other two libraries. This fact can impose severe restrictions on reactivity calculations. On the other hand, the experimental values of β_{eff} were independent of the libraries and spectral densities used for the fit. JENDL 3.3 presents an excellent agreement with the experimental β_{eff} showing a C/E ratio of 1.000. The independence of the β_{eff} with the libraries indicates that fixing β_1 and also the decay constants during the fitting procedure is not a serious restriction. Also, the β_{eff} measurement did not depend on the Diven factor and power normalization, two constants of very difficult experimental determination.

For the purposes of this work, the reflector effect can be neglected since its effect can only be noted for frequencies beyond β_{eff}/Λ and so the theoretical expressions for the spectral densities without the reflector are good enough.

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