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Measurements of Effective Delayed Neutron Fraction with External Neutron Source at Kyoto University Critical Assembly

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1. Introduction

Effective delayed neutron fraction (β_{eff}) characterizes the kinetic behavior of the nuclear reactor, and has been used in the subcriticality measurements to convert subcriticality in dollar unit to that in pcm unit. The calculation methodology by the eigenvalue calculations had been developed to evaluate β_{eff} accurately [1-2], and measurements of β_{eff} had been carried out to validate the calculated values by the noise analyses [3-4].

In the conventional methodology, β_{eff} has been obtained under an assumption that neutron source is set at the core center, and the neutron flux in fundamental mode is dominant over the core. Here, these β_{eff} are difficult to apply to the subcriticality evaluation with the use of external neutron source outside the core, because, in fact, the neutron flux distributions in the higher-mode components are considered easily induced, under an existence of external neutron source outside the core, such as the accelerator-driven system (ADS) at the Kyoto University Critical Assembly (KUCA). In the kinetic analyses [5-6], β_{eff} had been evaluated by taking into account the external neutron source defining the adjoint neutron flux in fixed-source calculations, however, no attempts are made to obtain β_{eff} by the measurements.

The purpose of this study was to examine the applicability of conventional measurement methodology of β_{eff} with the use of external neutron source.

2. Experimental Settings

2.1 Core configuration

Experiments on the measurement of β_{eff} were carried out at the KUCA A-core which is solid-moderated and -reflected one as shown in **Fig. 1**. The core was composed of the assemblies of normal fuel rod "F", partial fuel rod "4", and polyethylene reflector rod. Both fuel rods "F" and "4" were composed of 93% highly-enriched uranium and polyethylene moderator, and had a H/U value of 51.6. An americium-beryllium (Am-Be: Fig. 1) neutron source was installed outside the core as an external source with a neutron emission rate of 4.13E+06 n/s.

At a critical state, both excess reactivity and control rod worth (C1, C2 and C3) were measured by the positive period method and the rod drop method, respectively. And measured subcriticality in dollar unit was used in the measurements of β_{eff}, by the Nelson number method with the use of a ^{3}He detector installed outside the core. To examine the applicability of the measurement methodology with the variation of the subcriticality, subcriticality was ranging between 0.7 and 2.8 $ by the insertion of the control and the safety rods as shown in **Table I**.

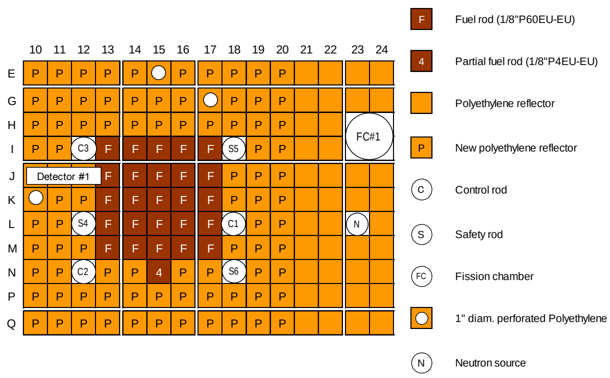

Fig. 1 Core configuration.

Table I Measured subcriticality deduced by the positive period method and the rod drop method.

	Rod insertion	Subcriticality [$]
Case I	C1	0.777 ± 0.026
Case II	C1, C2, C3	1.269 ± 0.030
Case III	C1, C2, C3, S4	2.286 ± 0.039
Case IV	C1, C2, C3, S4, S5, S6	2.777 ± 0.043

2.2 Measurement methodology

Among β_{eff} measurement methodologies, the Nelson number method based on the Rossi-α method can be applied to the measurements without the detector efficiency and the neutron life time. In the Rossi-α method, the probability that a neutron is detected, after the detection of another one with a time interval *dt*, is expressed as follows:

$$P(t)\,dt = C\,dt + Ae^{\alpha t}\,dt \quad , \tag{1}$$

where α is the prompt decay constant, *C* average count rate of the detector, and *A* correlation amplitude. The relationship between three parameters to β_{eff} and the subcriticality in dollar unit $\rho_{\$}$ can be expressed by defining the Nelson number *N* as follows:

$$N = -\left(\frac{2g^*S}{g\nu_p\Gamma}\right)\left(\frac{A}{\alpha C}\right) = -\left(\frac{1-\beta_{eff}}{\beta_{eff}}\right)\left[\frac{\rho_{\$}}{(1-\rho_{\$})^2}\right] \quad , \tag{2}$$

where ν_p means the average number of prompt neutrons released per fission, Γ neutron dispersion factor, *S* source intensity. *g* is a correction factor taking into account the variation in the probability of detecting correlated counts originating from neutrons of different worth, and *g** is a correction factor for the spatial and energy distribution of the source neutrons as follows:

$$g = \frac{\int \mathbf{P}(\mathbf{r})\,d\mathbf{r} \int \mathbf{P}(\mathbf{r})\,\mathbf{I}^2(\mathbf{r})d\mathbf{r}}{\left(\int \mathbf{P}(\mathbf{r})\mathbf{I}(\mathbf{r})d\mathbf{r}\right)^2} \quad , \tag{3}$$

$$g^* = \frac{\int \mathbf{s}(\mathbf{r})\,\mathbf{I_q}(\mathbf{r})\,d\mathbf{r} \int \mathbf{P}(\mathbf{r})\,d\mathbf{r}}{\int \mathbf{P}(\mathbf{r})\,\mathbf{I}(\mathbf{r})\,d\mathbf{r} \int \mathbf{s}(\mathbf{r})\,d\mathbf{r}} \quad , \tag{4}$$

$$\mathbf{P}(\mathbf{r}) = \int \Sigma_f(\mathbf{r},E)\,\phi(\mathbf{r},E)\,dE \quad , \tag{5}$$

$$\mathbf{I}(\mathbf{r}) = \int \chi(\mathbf{r},E)\,\phi^+(\mathbf{r},E)\,dE \quad , \tag{6}$$

$$\mathbf{I_q}(\mathbf{r}) = \int \chi_q(\mathbf{r},E)\,\phi^+(\mathbf{r},E)\,dE \quad , \tag{7}$$

where **s** is neutron source strength per unit volume at position **r**, ϕ and ϕ^+ forward and adjoint fluxes, Σ_f the macroscopic fission cross section, χ and χ_q are the fission spectrum and the spectrum of external neutron source, respectively. Solving Eq. (2) for β_{eff}, β_{eff} can be obtained from the Nelson number and subcriticality in dollar units as follows:

$$\beta_{eff} = \frac{\rho_{\$}}{N(1-\rho_{\$})^2 - \rho_{\$}} \quad . \tag{8}$$

3. Results and discussion

In the preparation of an estimation of β_{eff} by the Nelson number method, correction factors g and g* were obtained by the diffusion calculations (SRAC-CITATION [7]) in two dimensional (*x*-*y*) and 107 energy groups with JENDL-4.0 [8] as shown in **Table II**. From the results in Table 2, the correction factor *g* was observed to be constant. Conversely, a large correction was needed for neutron source with *g** indicating much smaller values with a variation, because the external neutron source was located outside the core and source efficiency was differed by the insertion of the control rods. And, the *g** values were strongly affected by the rod insertion pattern compared with the *g* values.

β_{eff} was obtained by two correction factors in Eq. (2) with the variation of the subcriticality, and measured β_{eff} were compared with ones obtained by the eigenvalue calculations with the use of MCNP6.1 [9] together with JENDL-4.0, as shown in **Table III**. Measured β_{eff}, involving the error of measured subcriticality and fitted curve for the estimation of the parameters *A*, *C* and α, showed good agreement with calculated ones around the relative difference of 5%, indicating that the correction factors were accurately estimated even if the external neutron source located outside the core. These results revealed a possibility to apply to a measurement in case of an installation of external neutron source outside the core.

Table II Variation of correction factors *g* and *g**

	g	*g**
Case I	1.05E+00	1.02E-02
Case II	1.05E+00	1.03E-02
Case III	1.05E+00	1.06E-02
Case IV	1.05E+00	8.63E-03

Table III Effective delayed neutron fraction β_{eff}

	Nelson number method	MCNP6.1
Case I	810 ± 18	785 ± 21
Case II	781 ± 15	791 ± 21
Case III	780 ± 18	836 ± 22
Case IV	801 ± 18	781 ± 21

4. Conclusions

Measurements of β_{eff} by the Nelson number method were conducted to examine its applicability with the use of external neutron source. Results of the measured β_{eff}

showed good agreement with those of calculated ones, indicating the applicability of the measurements to the existence of external neutron source outside the core.

As a future work, the measurements of β_{eff} by the pulsed neutron method could be attempted to be carried out in the ADS experiments to examine the dependence of β_{eff} with the variation of spectrum of external neutron source and subcriticality.

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References

1. Nauchi Y, Kameyama T. Proposal of direct calculation of kinetic parameters β_{eff} and Λ based on continuous energy Monte Carlo method. J. Nucl. Sci. Technol. 2005; 42; 503-514.
2. Meulekamp RK, Van der Marck S C. Calculating the effective delayed neutron fraction with Monte Carlo. Nucl. Sci. Eng. 2006; 152; 142-148.
3. Spriggs GD, Two Rossi-α techniques for measuring the effective delayed neutron fraction: Nucl. Sci. Eng. 1993; 113: 161-172.
4. Spriggs GD, A measurement of the effective delayed neutron fraction of the Westinghouse Idaho Nuclear Company slab tank assembly using Rossi-α techniques: Nucl. Sci. Eng. 1993; 115: 76-80.
5. Ravetto P, Rostagno M M. Application of the mutipoint method to the kinetics of accelerator-driven systems. Nucl. Sci. Eng. 2004; 148; 79-88.
6. Gandini A. ADS subcriticality evaluation based on the generalized reactivity concept. Ann. Nucl. Energy. 2004; 31; 213-821.
7. Okumura K, Kugo T, Kaneko K, *et. al*. A comprehensive neutronics calculation code system, JAERI-Data/Code 2007004. Ibaraki-ken (Japan): Japan Atomic Energy Agency; 2006.
8. Shibata K, Iwamoto O, Nagaya T, et al., “JENDL-4.0: A new library for nuclear science and technology,” J. Nucl. Sci. Technol., 48, 1(2011).
9. Goorley JT, James MR, Booth TE, et al., “Initial MCNP6 release overview – MCNP6 version 1.0,” LA-UR-13-22934, (2013).