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The Verification of Modified Neutron Source Multiplication Method for AGN-201 reactor

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1. Introduction

The modified Neutron Source Multiplication (NSM) method has been proposed for subcriticality measurement of a reactor system [1-5]. This method modifies the conventional NSM method with fundamental mode extraction and uses three correction factors mainly. In the present study, the subcriticality was evaluated for Aerojet General Nucleonis (AGN)-201 reactor by the modified NSM method. TRANSX code is used to assign cross section table with MATXS format and PARTISN simulation code is used for both eigenvalue problem and fixed source problem. [4-5]

2. Method and Correction Factors

In modified NSM method, the key expression that explicitly describes the relation between the contents of the respective modes in $\boldsymbol{\varphi}^s(\mathbf{r})$ and their subcriticalities can be derived as

$$\boldsymbol{\varphi}^s(\mathbf{r}) = \left(\frac{1}{\rho^s}\right)\left(\boldsymbol{\varphi}_1^{c\dagger},\mathbf{s}\right)\frac{\boldsymbol{\varphi}_1^c(\mathbf{r})}{\left(\boldsymbol{\varphi}_1^{c\dagger},\mathbf{F}\boldsymbol{\varphi}_1^c\right)} + \sum_{i=2}^{\infty}\left(\frac{1}{\rho_i^s}\right)\left(\boldsymbol{\varphi}_i^{c\dagger},\mathbf{s}\right)\frac{\boldsymbol{\varphi}_i^c(\mathbf{r})}{\left(\boldsymbol{\varphi}_i^{c\dagger},\mathbf{F}\boldsymbol{\varphi}_i^c\right)}$$
$$= \left(\frac{1}{\rho^s}\right)\left(\boldsymbol{\varphi}_1^{c\dagger},\mathbf{s}\right)\overline{\boldsymbol{\varphi}}_1^c(\mathbf{r}) + \sum_{i=2}^{\infty}\left(\frac{1}{\rho_i^s}\right)\left(\boldsymbol{\varphi}_i^{c\dagger},\mathbf{s}\right)\overline{\boldsymbol{\varphi}}_i^c(\mathbf{r}) \quad (1)$$

Here the first term of the right-hand side of Eq. (1) is the fundamental mode component and it consists of three terms: (i) the inverse of subcriticality, (ii) the neutron source intensity weighted by the adjoint flux (effective source intensity) and (iii) the distribution of fundamental mode normalized by the total number of fissions.

The fundamental mode component can be extracted from $\boldsymbol{\varphi}^s(\mathbf{r})$ and it would be contributed as a component in detector count rate and hence

$$M_1 = \left(\frac{1}{\rho^s}\right)\left(\boldsymbol{\varphi}_1^{c\dagger},\mathbf{s}\right)\int_V \mathbf{W}_d(\mathbf{r})\overline{\boldsymbol{\varphi}}_1^c(\mathbf{r})d\mathbf{r}\ , \quad (2)$$

where $W_d(\mathbf{r})$ is the weighting factor denoting a degree of contribution of neutrons at $\mathbf{r}$ in the core region to the detector. In order to estimate the subcriticality of a specific state, it is needed to compare with a selected reference state whose subcriticality was already known. Consequently,

$$\frac{M_{1,l}}{M_{1,ref}} = \frac{\left(\frac{1}{\rho_l^s}\right)\left(\boldsymbol{\varphi}_{1,l}^{c\dagger},\mathbf{s}\right)\int_V \mathbf{W}_d(\mathbf{r})\overline{\boldsymbol{\varphi}}_{1,l}^c(\mathbf{r})d\mathbf{r}}{\left(\frac{1}{\rho_{ref}^s}\right)\left(\boldsymbol{\varphi}_{1,ref}^{c\dagger},\mathbf{s}\right)\int_V \mathbf{W}_d(\mathbf{r})\overline{\boldsymbol{\varphi}}_{1,ref}^c(\mathbf{r})d\mathbf{r}} \quad . \quad (3)$$

Finally, it can be obtained as

$$\rho_l^s = \rho_{ref}^s \frac{\left(\boldsymbol{\varphi}_{1,l}^{c\dagger},\mathbf{s}\right)}{\left(\boldsymbol{\varphi}_{1,ref}^{c\dagger},\mathbf{s}\right)} \frac{\int_V \mathbf{W}_d(\mathbf{r})\overline{\boldsymbol{\varphi}}_{1,l}^c(\mathbf{r})d\mathbf{r}}{\int_V \mathbf{W}_d(\mathbf{r})\overline{\boldsymbol{\varphi}}_{1,ref}^c(\mathbf{r})d\mathbf{r}} \frac{M_{1,ref}}{M_{1,l}}$$
$$= \rho_{ref}^s \frac{C_{1,ref}}{C_{1,l}} \frac{\left(\boldsymbol{\varphi}_{1,l}^{c\dagger},\mathbf{s}\right)}{\left(\boldsymbol{\varphi}_{1,ref}^{c\dagger},\mathbf{s}\right)} \frac{\int_V \mathbf{W}_d(\mathbf{r})\overline{\boldsymbol{\varphi}}_{1,l}^c(\mathbf{r})d\mathbf{r}}{\int_V \mathbf{W}_d(\mathbf{r})\overline{\boldsymbol{\varphi}}_{1,ref}^c(\mathbf{r})d\mathbf{r}} \frac{M_{ref}}{M_l} \quad (4)$$
$$= \rho_{ref}^s C_l^{ext} C_l^{im} C_l^{sp}\left(\frac{M_{ref}}{M_l}\right) \quad .$$

2.1 Purposes and Physical meanings

The extraction correction factor is used to extract the fundamental mode and it is the discrepancy between extracted fundamental component fractions of reference state and current subcritical state.

The effective source intensity varies when the distribution of adjoint flux changes: if the value of adjoint flux increases at the place where external neutron sources are located, the intensity also increases. In the modified NSM method, the importance field correction factor is introduced to correct the effect caused by the disturbance of neutron importance field and it is the discrepancy between effective source intensities of two subcriticality states, i.e. the reference and current subcriticality state.

In subcriticality measurements, the distribution of the fundamental mode sometime changes significantly and locally, for example, in such a case when a control rod bank insertion pattern is changed. The field of view of a neutron detector is normally narrow and therefore it sees only its vicinity. When the neutron detector is located near to the place where control rods are inserted or withdrawn, its count rate changes largely due to local perturbation. When the control rods located far from the neutron detector are inserted or withdrawn, the count rate would change insensitively. The spatial correction factor corrects the effects of local perturbation induced in the distribution of the fundamental mode and, in some cases, the insensitiveness aforementioned. Therefore the spatial correction factor is the discrepancy between the normalized fundamental mode distributions for reference state and current subcritical state.

2.2 Mathematical Meanings

According to the mathematical expressions, three correction factors can be defined as follow.

The extraction correction factor is defined as the ratio of the extraction coefficient of the fundamental mode for the reference state to that for a specific state.

The importance field correction factor is the ratio of the effective source intensity for a specific state to that for the reference state.

The spatial correction factor is the ratio of normalized fundamental mode component contained in the neutron count rate for a specific state to that for the reference state.

2.3 Characteristics

The dependence of the correction factors on the net withdrawal step of control rod bank is a very complicated manner as seen in Table 1. Nevertheless, in the previous studies, it was found that the product of all factors varies very smoothly with respect to the net withdrawal steps when many subcritical states were considered. Therefore it can be expressed or given approximately as a smooth interpolation over the withdrawal bank positions for other applications such as the continuous subcriticality monitoring using digital reactivity meter [6].

3. Evaluation of Subcriticality

To estimate the subcriticality exactly, three kinds of correction factors were evaluated using the flux informations such as forward, adjoint and fixed source fluxes, in both eigenvalue problem and fixed source problem. Here it is needed to select a state nearest to the criticality as a reference state. This is because to be able to determine the reference subcriticality exactly with some conventional method. Then the subcriticalies for the several subcriticality states were evaluated using neutron count rate.

4. Results

Table 1 lists the selected subcriticality states, the relevant k-eff values that were obtained by solving the eigenvalue problem, theoretical subcriticalities related to the k-eff values, the neutron counting multiplications, the numerical values of three correction factors in each subcriticality state, estimated subcriticalities by the modified NSM method and their relative percentage errors compared with theoretical values.

5. Conclusion

It was verified that the applicability of the modified NSM method with fundamental mode extraction to the subcriticality measurement of AGN-201 reactor. The modified NSM method is economical and simple one among the several subcriticality measurement methods. Based on the previous studies, it can be recommended that the modified NSM method can be used for not only subcriticality measurement or control rod worth measurement but also continuous subcriticality monitoring during criticality approach by combining with the methodology of digital reactivity meter.

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Table 1. Subcriticality applied three correction factors

Case	k_{eff}	Theoretical ρ [%Δk/k]	Q	C^{ext}	C^{im}	C^{sp}	ρ [%Δk/k]	Error [%]
C21F00	1.0077	-7.6018e-3						
C18F00	1.0047	-4.6483e-3	1.64026	0.99016	0.79601	1.01445	-3.7056e-3	20.28
C12F00	0.9993	6.7045e-4	-11.43284	0.99023	1.05989	1.01704	7.0973e-4	-5.85
C06F00	0.9961	3.9254e-3	-1.95910	0.98267	0.97921	1.02585	3.8302e-3	2.42
C00F00	0.9946	5.4597e-3	-1.41068	0.98567	1.01201	1.01392	5.4501e-3	0.17