Estimation of Control Rod Worth of CNP1000 Reactor using the Modified Neutron Source Multiplication Method

Jiahe Bai [a,b], Ser Gi Hong [b*], Chenghui Wan [a], Yunzhao Li [a]
[a]*School of Nuclear Science and Technology, Xi'an Jiaotong University, 28 Xianning west road, Xi'an, China*
[b]*Dept. Of Nuclear Engineering, Hanyang University, 222 Wangsimini-ro, Seongdong-gu, Seoul, Korea*
[*]*Corresponding author: hongsergi@hanyang.ac.kr*

1. Introduction

As one of the main reactivity control ways, the control rod plays an important role in the reactor safety and reactor control. During the zero-power physics test at the BOL (Beginning Of Life), the control rod worth would be measured. There are three kinds of traditional method for determining the control rod worth, including boron dilution method, rod swap method and dynamic rod worth measurement [1,2]. However, these three methods are capable to be applied only after the reactor reaches the critical state. If the control rod worth measurement could be implemented under subcritical states, lots of time could be saved for the commercial reactors. Therefore, the modified neutron source multiplication method with a fundamental mode extraction [3,4] is utilized to determine the control rod worth under subcritical state. In this work, the modified neutron source multiplication method is applied to estimate the control rod worth for CNP1000 reactor where the ex-core detector signals are simulated using a nodal diffusion calculation.

2. Methods and Results

In this section, the detailed method is described. Then, for verification, the CNP1000 reactor is modeled and the source-range detector signals are simulated under subcritical state. The control rod worth results through this method are also compared with the static control rod worth obtained from static eigenvalue calculations with nodal diffusion method.

2.1 Theory model

Under subcritical state, the external neutron sources existing in the reactor core can't be ignored, which influences the flux shape to a large extent. Therefore, the fixed-source equation is considered here,

$$\boldsymbol{L}\boldsymbol{\phi}^s(r)=\boldsymbol{F}\boldsymbol{\phi}^s(r)+\boldsymbol{s}(r) \tag{1}$$

where $\boldsymbol{\phi}^s(r)$ is the true flux distribution under subcritical state. The $\boldsymbol{s}(r)$ contains all the external neutron sources, such as primary neutron source, secondary neutron source, delayed neutron source, and self-spontaneous neutron source.

The neutron diffusion equation for eigenvalue problem is given as follows :

$$\boldsymbol{L}\boldsymbol{\phi}_i^e(r)=\frac{1}{k_i}\boldsymbol{F}\boldsymbol{\phi}_i^e(r) \qquad i=1,2,\cdots,\infty \tag{2}$$

where k_i is the i-th eigenvalue, and ϕ_i^e is the i-th eigenfunction and the adjoint neutron diffusion equation is given by

$$\boldsymbol{L}^*\boldsymbol{\phi}_i^{e*}(r)=\frac{1}{k_i}\boldsymbol{F}^*\boldsymbol{\phi}_i^{e*}(r) \qquad i=1,2,\cdots,\infty \tag{3}$$

where ϕ_i^{e*} is the i-th adjoint eigenfunction.

The $\boldsymbol{\phi}^s(r)$ from fixed-source equation could be expanded by the eigenfunction ϕ_i^e as follows :

$$\boldsymbol{\phi}^s(r)=\sum_{i=1}^{\infty}A_i\boldsymbol{\phi}_i^e(r). \tag{4}$$

Substituting the expansion form of Eq.(4) into Eq. (1) gives the following expression :

$$\boldsymbol{\phi}^s(r)=\sum_{i=1}^{\infty}\frac{k_i}{1-k_i}\left(\boldsymbol{\phi}_i^{e*},\boldsymbol{s}\right)\left[\frac{\boldsymbol{\phi}_i^e(r)}{\left(\boldsymbol{\phi}_i^{e*},\boldsymbol{F}\boldsymbol{\phi}_i^e\right)}\right]. \tag{5}$$

The fundamental mode contained in the $\boldsymbol{\phi}^s(r)$ has the following form, which establishes the relationship between $\boldsymbol{\phi}^s(r)$ and fundamental eigenvalue k_1.

$$\boldsymbol{\phi}_1^s(r)=\frac{k_1}{1-k_1}\left(\boldsymbol{\phi}_1^{e*},\boldsymbol{s}\right)\left[\frac{\boldsymbol{\phi}_1^e(r)}{\left(\boldsymbol{\phi}_1^{e*},\boldsymbol{F}\boldsymbol{\phi}_1^e\right)}\right]. \tag{6}$$

Under subcritical state, the source-range detector is utilized to measure signal. The simulated detector signal could be represented as follows [5] :

$$M=\sum_V\omega_f(r)\sum_{g=1}^{G}\nu\Sigma_{f,g}\phi_g^s(r), \tag{7}$$

where ω_f(r) is the response function for the ex-core detector.

The fundamental mode part contained in the total simulated detector signals is represented as Eq.(8),

$$\begin{aligned}M_1&=\sum_V\omega_f(r)\sum_{g=1}^{G}\nu\Sigma_{f,g}\phi_{1,g}^s(r)\\&=\frac{k_1}{1-k_1}\left(\boldsymbol{\phi}_1^{e*},\boldsymbol{s}\right)\sum_V\omega_f(r)\sum_{g=1}^{G}\nu\Sigma_{f,g}\frac{\boldsymbol{\phi}_1^e(r)}{\left(\boldsymbol{\phi}_1^{e*},\boldsymbol{F}\boldsymbol{\phi}_1^e\right)}\end{aligned}. \tag{8}$$

Therefore, the fundamental extraction coefficient is defined to extract the fundamental detector signal from the total detector signal as follows :

$$C_1^s=\frac{M_1}{M}. \tag{9}$$

The neutron count multiplication factor is represented as the ratio of detector signals of any subcritical state to the reference state as follows :

$$Q_l = \frac{M_l}{M_{ref}} = C_l^{ext} C_l^{im} C_l^{sp} \frac{\rho_{ref}}{\rho_l}, \qquad (10)$$

where l is any subcritical state, C_l^{ext} is the extraction correction, C_l^{im} is the importance field correction, and C_l^{sp} is the spatial correction. Q_l is the neutron count multiplication factor which can be obtained from the measurement data of source-range detector. It could be observed that if the above three corrections could be calculated in advance, then the subcriticality at any subcritical state can be determined. The above method has been implemented in the core code named SPARK [6], which has the capability of core calculation based on the neutron diffusion solver.

2.2 CNP1000 model

The CNP1000 reactor is a three-loop PWR operated in China, with thermal capacity of 2895MW. This reactor loads 157 fuel assemblies in total with three fuel batches. The 17×17 square-pitch array is employed to fill the fuel assembly, with 264 fuel rods, 24 guide tubes, and 1 instrument tube. Two source-range detectors are contained outside the reactor vessel with a small oblique degree from the horizontal centerline in the radial and located at the lower half of the reactor in axial. The radial and axial configurations are shown as Fig. 1 and Fig. 2, respectively.

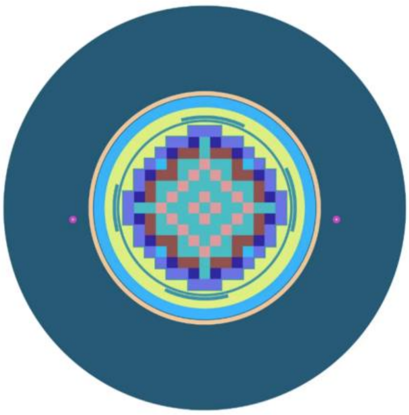

Fig. 1. Radial configuration of CNP1000 reactor

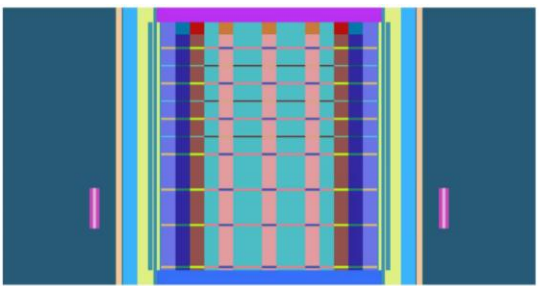

Fig. 2. Axial configuration of CNP1000 reactor

There are nine groups of control rods contained in the reactor core for reactivity control, which are divided into three types aiming for different functions, including power adjustment (G1, G2, N1, and N2), temperature adjustment (R), and reactor shutdown (SA, SB, SC, and SD). The control rods G1 and G2 are grey control rods, and the others are black control rods. The configuration of control rods is presented in **Fig. 3**.

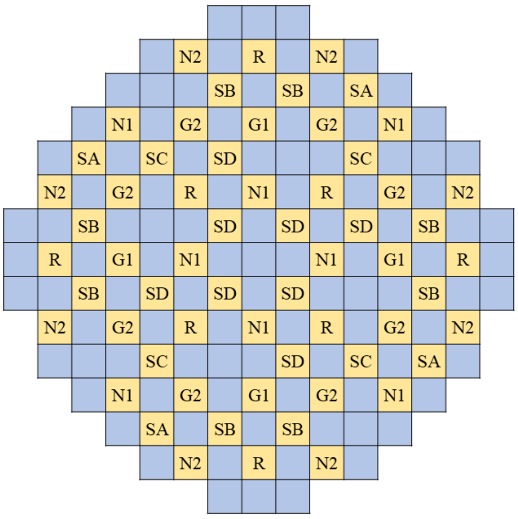

Fig. 3 Control rod configuration of CNP1000 reactor

2.3 Application results

In this study, the source-range detector signals are simulated results, which are calculated by SPARK. Considering six states here, and corresponding control rod positions are shown in Table I. The 225 step and 0 step mean the control rod is at the top and bottom of the core, respectively. For these six states, the SA, SB, SC and SD are at 225 step. The state 6 is the reference state.

Table I: Control rod position for subcritical states

State	N2	N1	G2	G1	R
State 1	5	5	5	5	5
State 2	5	5	5	225	5
State 3	5	5	225	225	5
State 4	5	225	225	225	5
State 5	225	225	225	225	5
State 6 (ref)	225	225	225	225	225

Two fuel assemblies in this reactor core contain the Sb-Be external source. The source intensity is set up 1.32e10. The locations for these two fuel assemblies are shown in Fig. 4.

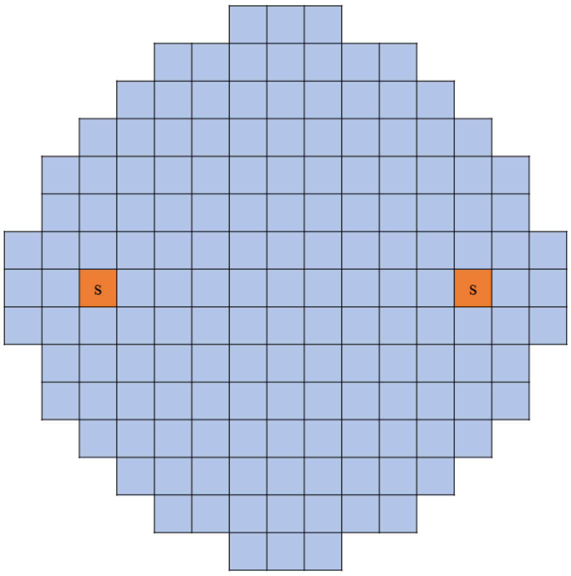

Fig. 4 Locations of external sources

The reference eigenvalues and subcriticality for these six subcritical states are calculated by SPARK, which are shown in Table II.

Table II: Reference eigenvalues and subcriticality

State	k_{eff}	ρ
State 1	0.92897	0.07646
State 2	0.93805	0.06604
State 3	0.94846	0.05435
State 4	0.95572	0.04633
State 5	0.95879	0.04298
State 6 (ref)	0.96974	0.03120

Three corrections (C_l^{ext}, C_l^{im}, C_l^{sp}) for these subcritical states are illustrated in Table III. There are two source-range detectors contained in this reactor, thus the corrections for these two detectors are shown together.

Table III Results of the correction factors

State	SR	C_l^{ext}	C_l^{im}	C_l^{sp}
State 1	SR1	1.3255	0.7759	0.9523
	SR2	1.3256	0.7759	0.9523
State 2	SR1	0.9397	1.0761	0.9823
	SR2	0.9400	1.0754	0.9823
State 3	SR1	1.2224	0.8580	0.7888
	SR2	1.2228	0.8574	0.7888
State 4	SR1	1.2337	0.7379	0.8015
	SR2	1.2343	0.7373	0.8015
State 5	SR1	1.1538	0.7036	0.8840
	SR2	1.1543	0.7030	0.8840

The above correction factors are applied to the simulated source-range detector signals as Eq. (10). Therefore, the estimated eigenvalue for these subcritical states could be obtained by the present method, which are shown in Table IV. It is observed there is no deviattion between the estimated results and the reference results, indicating the estimated results consistent with the reference results.

Table IV: Estimated eigenvalue and subcriticality

State	Estimated k_{eff}	Estimated ρ
State 1	0.92897	0.07646
State 2	0.93805	0.06604
State 3	0.94846	0.05435
State 4	0.95572	0.04633
State 5	0.95879	0.04298

The objective of this study is to gain the control rod worth under subcriticality states. Therefore, the final results are control rod worth comparison between the reference values and the estimated values shown in Table V. It is observed that the estimation of control rod worth agrees well with the reference results, indicating this present method could achieve good performance in determining control rod worth under subcritical states.

Table V: Performance of control rod worth estimation

CR	SR	Reference rod worth (pcm)	Estimated rod worth (pcm)	Absolute bias (pcm)	Relative bias (%)
G1	SR1	1042	1042	0	0
	SR2	1042	1042	0	0
G2	SR1	1169	1169	0	0
	SR2	1169	1169	0	0
N1	SR1	802	802	0	0
	SR2	802	802	0	0
N2	SR1	334	334	0	0
	SR2	334	334	0	0
R	SR1	1178	1178	0	0
	SR2	1178	1178	0	0

3. Conclusions

The modified neutron source multiplication method with a fundamental mode extraction was successfully applied to estimate the control rod worth with the

SPARK code to provide the extraction correction, importance field correction, and spatial correction. These three correction factors were applied to the simulated source-range detector signals to gain the estimated eigenvalue as well as estimated control rod worth. The verification results showed the estimated results agree well with the reference results, indicating this present method is a promising approach for determining the control rod worth under subcritical states.

REFERENCES

[1] Y.A. Chao, D.M. Chapman, D.J. Hill, et al., Dynamic Rod Worth Measurement, Nuclear Technology, Vol. 132, p. 403-412, 2000.

[2] E.K. Lee, H.C. Shin, S.M. Bae, et al., New dynamic method to measure rod worths in zero power physics test at PWR startup, Annals of Nuclear Energy, Vol. 32, p. 1457-1475, 2005.

[3] M. TSUJI, N. SUZUKI, Y. SHIMAZU, Subcriticality Measurement by Neutron Source Multiplication Method with a Fundamental Mode Extraction, Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 40, No. 3, p.158-168, 2003.

[4] W. NAING, M. TSUJI, Y. SHIMAZU, Subcriticality Measurement of Pressurized Water Reactors by the Modified Neutron Source Multiplication Method, Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 40, No. 12, p. 983-988,2003.

[5] M.W. Crump, J. C. Lee, Calculation of Spatial Weighting Functions for Ex-Core Neutron Detectors, Nuclear Technology, Vol. 41, No. 1, p. 87-96,1978.

[6] C. Wan, Y. Li., et al., Code Development and Engineering Validation of PWR Fuel Management Software Bamboo-C, Nuclear Power Engineering, Vol. 42, No. 5, p. 15-22, 2021.