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Evaluation of Effective Delayed Neutron Fraction of RTP using MCNP

M. H. Rabir [a], C. J. Hah [a*]
[a]*KEPCO Internaltional Nuclear Graduate School*
[*]*Corresponding author: changhah@kings.ac.kr*

1. Introduction

Effective delayed neutron fraction, β_{eff}, has an important role for a nuclear reactor power control. It has been used in point kinetics equation to measure the reactivity change of the nuclear reactor. MCNP starting from version 4C has been enabled to evaluate β_{eff} based on static calculation. Several methods have been proposed for the evaluation of β_{eff} with Monte Carlo method. Most of these methods have required modifying MCNP code. The prompt perturbation method needs huge computation time. Nevertheless this is not an important issue as the typical MNCP computation time is decreasing rapidly with the development of high speed computer system. The purpose of this paper is to systematically evaluate β_{eff} for annular 1000 kW RTP TRIGA Mark II cores (Core-0 and Core-14) with different type of fuel loading, using MCNP code.

2. Description of RTP Core

The Malaysian 1MW PUSPATI TRIGA Reactor (RTP) was designed to do researches on neutron and gamma radiation studies as well as for isotope production, activation, and student training. RTP has been used mainly for beam experiments, samples analyses, education and trainings.

2.1 RTP Core Model

RTP has reached its first criticality on 28th of Jun in 1982. It loaded standard TRIGA $UZrH_{1.6}$ fuels with 8.5 wt%, 12 wt% and 20 wt% of uranium fuel. Enrichment of ^{235}U in uranium fuel is 19.7 %. It is cylindrical core surrounded with graphite reflector and cooled by natural convection. Both top grid plate and bottom grid plate are made of Al-6061. RTP has 4 control rods which are made of boron carbide as shown in Table I. Three of them are fuel follower type and the other is air follower type. The fuel follower control rods (FFCR) consist of 8.5 wt% of uranium and B_4C absorber on top of the fuel section. The reactor utilizes hydride fuel, homogeneous mixture of uranium and zirconium hydride ($UZrH_{1.6}$). The $ZrH_{1.6}$ is used as main moderator above 0.14 eV of neutron energy. The cross-sectional view of Core-14 and Core-0 is shown in Figure 1 and Figure 2. Fuel elements are arranged in seven circular rings in the core and the spaces between the fuel elements are filled with water that acts as coolant and moderator.

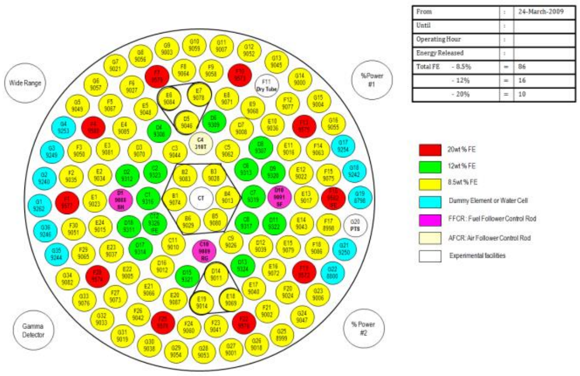

Fig. 1 RTP Core-14 configuration.

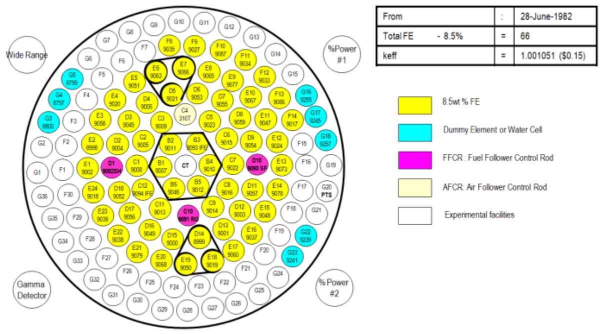

Fig. 2. RTP Core-0 configuration.

2.2 Effective Delayed Neutron Fraction

(1) General Definition of β_{eff}

Effective delayed neutron fraction in a critical system can be simply derived as the ratio of the effective production of delayed neutron to the effective production of total neutron [1] :

$$\beta_{eff} = \frac{\sum_m \sum_i \nu_{d,i}^m \langle\langle \varphi^*(r,E) \chi_{d,i}^m(E) \langle \Sigma_f^m(r,E') \phi(r,E') \rangle_{E'} \rangle_E \rangle_r}{\sum_m \langle\langle \varphi^*(r,E) \chi_t^m(E) \langle \nu_t^m(E') \Sigma_f^m(r,E') \phi(r,E') \rangle_{E'} \rangle_E \rangle_r} \quad (1)$$

where m, i, d and t denote fissile index, delayed neutron group index and total neutron respectively. Equation (1) needs adjoint flux as a weighting function to evaluate effective delayed neutron fraction.

(2) Prompt Perturbation Method

The prompt perturbation method was first proposed by M. M. Bretscher [2]. The perturbation theory approach treats delayed neutrons as a perturbation from a reference system. If delayed neutrons produced by prompt neutron fission are considered as a perturbation in neutron balance equation, the perturbed system can be described as :

$$L\phi_p = \frac{1}{k_p}(F - F_d)\phi_p \qquad (2)$$

where $F_d\phi_p$ represents the perturbation, the number of delayed neutron produced after prompt neutron fission. The first order approximation of the perturbation theory with small perturbation [3] leads to:

$$\frac{k-k_p}{k} \cong \frac{\langle\phi^* F_d \phi\rangle}{\langle\phi^* F\phi\rangle} - \frac{k-k_p}{k}\frac{\langle\phi^* F\delta\phi\rangle}{\langle\phi^* F\phi\rangle} + \frac{k-k_p}{k}\frac{\langle\phi^* F_d\phi\rangle}{\langle\phi^* F\phi\rangle} \qquad (3)$$

where $\phi_p = \phi + \delta\phi$ and ϕ is unperturbed flux.
The first term of the right side in Equation (3) is equal to the definition of effective delayed neutron fraction in equation (1). Therefore, the effective delayed neutron fraction is approximated as :

$$\beta_{eff} \cong \frac{k-k_p}{2k-k_p}\left(1 + \frac{\langle\phi^* F\delta\phi\rangle}{\langle\phi^* F\phi\rangle}\right) \qquad (4)$$

Equation (4) shows additional term, different from equation in references [1] and [4], which accounts for the source of error in the prompt perturbation method.

Table I. TRIGA fuel element and control rod.

	Fuel Element	Fuel Follower Control Rod
Geometrical data		
Radius of Zr rod (cm)	0.3175	0.3175
Radius of fuel (cm)	1.765	1.665
Air gap (cm)	0.05	0.05
Cladding (cm)	0.05	0.05
Fuel composition		
Mass of uranium		
Mass of U^{235}		
Uranium (wt%)	8.5, 12, 20	8.5
Enrichment (wt%)	19.7	19.7
H:Zr ratio	1.6	1.6
Absorber		B_4C
Natural Boron (%)		80%

2.3 Calculation Results

Effective delayed neutron fraction, β_{eff}, was calculated using MCNP5 with ENDF-VII library. The MCNP calculations were run with 2,500,000 active histories. A total of 5,000 histories per generation were used and 500 generations of neutrons. The first 10 generations were skipped to obtain a well-distributed neutron source. The MCNP result for the perturbed case shows k_p = 0.99554 ± 0.00045, using only prompt neutron history. The MCNP result for the unperturbed case shows total effective multiplication factor, k = 1.00280 ± 0.00045 which includes both prompt neutron and delayed neutron history. Using equation (4), the effective delayed neutron fraction of RTP, β_{eff} , was calculated using the unperturbed multiplication factor k and the perturbed multiplication factor k_p. The standard deviations of multiplication factors are 0.00045 for Core-0 and 0.00048 for Core-14, respectively. The results are shown in Table II and the reference value of β_{eff} were obtained from the manufacturer of RTP, GA (General Atomic). The reference value, 0.0070 is currently used for RTP operation.

Table II. Calculated β_{eff} of RTP

	Ref.	Core-0	Core-14
k		1.00280±0.00045	1.12747±0.00048
k_p		0.99554±0.00045	1.11942±0.00048
β_{eff}	0.0070	0.00719±0.00090	0.00709±0.00096
Diff.		0.00019	0.00009

3. Conclusions

The difference of β_{eff} is 0.00019 for Core-0, 0.00009 for Core-14. The results shown in this paper are better than other papers results. In reference [5], β_{eff} difference is 0.00080 for 250kW TRIGA Mark II in Ljubljana. In reference [1], the difference is 0.0007 for VR-1 training reactor in Prague using the same prompt perturbation method. Major part of error in prompt perturbation method originates from the exclusion of prompt neutron generated by delayed neutron.

The second term in the parenthesis in equation (4) accounts for prompt neutron source induced by delayed neutron and is always negative. Exact form of equation (4) still has error resulting from the second order terms of the perturbation theory that should be included for exactness.

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