Nuclear Engineering and Technology 48 (2016) 1120–1125

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Investigating Dynamic Parameters in HWZPR Based on the Experimental and Calculated Results

Zahra Nasrazadani[*], *Manochehr Behfarnia*, *Jamshid Khorsandi*, and *Mohammad Mirvakili*

Reactors Research School, Nuclear Science And Technology Research Institute, Atomic Energy Organization of Iran,
Post Box Number 81465/1589, Esfahan, Iran

ARTICLE INFO

Article history:
Received 23 September 2015
Received in revised form
15 March 2016
Accepted 29 March 2016
Available online 16 April 2016

Keywords:
Delayed Neutron Fraction
HWZPR
Monte Carlo N-Particle Code
Noise Analysis
Variance to Mean Ratio

ABSTRACT

The neutron decay constant, α, and effective delayed neutron fraction, β_{eff}, are important parameters for the control of the dynamic behavior of nuclear reactors. For the heavy water zero power reactor (HWZPR), this document describes the measurements of the neutron decay constant by noise analysis methods, including variance to mean (VTM) ratio and endogenous pulse source (EPS) methods. The measured α is successively used to determine the experimental value of the effective delayed neutron fraction as well. According to the experimental results, β_{eff} of the HWZPR reactor under study is equal to 7.84e-3. This value is finally used to validate the calculation of the effective delayed neutron fraction by the Monte Carlo methods that are discussed in the document. Using the Monte Carlo N-Particle (MCNP)-4C code, a β_{eff} value of 7.58e-3 was obtained for the reactor under study. Thus, the relative difference between the β_{eff} values determined experimentally and by Monte Carlo methods was estimated to be < 4%.

1. Introduction

The heavy water zero power reactor (HWZPR) is a low power research reactor. The reactor is used to train power reactor operators and to provide an experimental base for research studies on the physics of heavy water reactors as well as for nuclear code validation. The nominal thermal flux of HWZPR is about 10^8(n/cm^{-2}s^{-1}). The HWZPR is located at the nuclear engineering department of a reactor school in Isfahan, Iran.

The importance of delayed neutrons on the reactor dynamics can be understood through their impact on the reactor power change rate. Even if delayed neutrons constitute only a very small fraction of the total number of neutrons, they play a dominant role in the fission chain reaction control. Therefore, the exact determination of the effective delayed neutron fraction, β_{eff}, value is the main requirement in the field of reactor physics. An accurate estimate ofβ_{eff} is essential for converting reactivity, as measured in dollars, to an absolute reactivity and to an absolutek_{eff}. Additionally, a valuable insight into the dynamic system behavior of a critical system can be attained through the measurement of the prompt neutron decay constant. Therefore, in this work by using noise

---

[*] *Corresponding author.*
E-mail address: zahranasr50@yahoo.com (Z. Nasrazadani).

http://dx.doi.org/10.1016/j.net.2016.03.013

analysis methods, such as the variance to mean (VTM) and endogenous pulse source (EPS) methods, the prompt decay constant α in different subcritical conditions, is measured and the results are plotted on a linear scale. The data forms a straight line and can be used to predict the value of α_0 at delay critical condition.

2. Reactor description

The HWZPR employs metal natural uranium as fuel and heavy water as a moderator. Its core is installed in a cylindrical tank, 240 cm in diameter and 300 cm in height. The reactor tank is surrounded by a 75 cm thick graphite reflector. There are 124 fuel rods (each fuel rod contains 20 fuel pellets), two control rods, and two safety rods. The height and diameter of each fuel pellet are 10 cm and 3.5 cm, respectively. The cladding is made of aluminum alloy with 0.1 cm thickness and covers each fuel pellet. Heavy water, 35 cm in depth, acts as a reflector under the fuel rods in the tank. Because of low nominal power, 10 W, and low heat production in the core, the vessel, cladding, and fuel tubes are made of aluminum alloy. This alloy has good mechanical properties and is resistant against corrosion and irradiation. The fuel rods and heavy water are kept under low pressure nitrogen gas to prevent humidity entering the core and to avoid heavy water degradation. The height and diameter of the active core are 205.2 cm and 238 cm, respectively. The fuel rods in the core are arranged in a square lattice with a pitch of 18 cm. The He^3 detector was used in the experiment and was placed in the Al guide tube in the core [1].

3. β_{eff} Monte Carlo calculation

There are different methods for calculating theβ_{eff}. In this work, the prompt method is used and the related expression for β_{eff} is [2,3]:

$$\beta_{eff} = \frac{\langle \chi_d \nu_d \rangle}{\langle \chi \nu \rangle} = 1 - \frac{\langle \chi \nu - \chi_d \nu_d \rangle}{\langle \chi \nu \rangle} \cong 1 - \frac{\langle \chi_p \nu_p \rangle}{\langle \chi \nu \rangle} \tag{1}$$

where ν andν_d, are average neutron and delayed neutron multiplicity per fission, respectively, χ is the energy spectrum of the total neutron, and χ_d is the energy spectrum of the delay neutron. The term $(\chi_d - \chi)\nu_d$ is two orders of magnitude smaller than the one with$\chi\nu_p$, because ν_d is two orders of magnitude smaller than ν_p. For the same reason, the shape of χ is almost equal to that ofχ_p, therefore the approximation in the last step is valid. Often it is simply stated that:

$$\frac{\langle \chi_p \nu_p \rangle}{\langle \chi \nu \rangle} = \frac{k_p}{k} \rightarrow \beta_{eff} \cong 1 - \frac{k_p}{k} \tag{2}$$

where k is the eigenvalue for all neutrons andk_p is the eigenvalue for prompt neutrons only.

This approach is based on an approximate formula of β_{eff} that essentially assumes that the "prompt" and "total" neutron fluxes can be considered as being practically the same.

3.1. *Calculation of β_{eff} in HWZPR*

Monte Carlo N-Particle (MCNP)-4C was used to simulate HWZPR configuration, in three dimensions. The continuous energy cross section data from LANL/T-2 and ENDF-VI libraries and S(α,β) thermal scattering model and the full continuous energy cross section available from the MCNP4 Library were used in the calculation. The three-dimensional model comprises all the reactor components such as the 124 fuel rods, upper and lower grid plates, annular graphite reflector, and aluminum tank. Because of the 18 cm step size of fuel rods, the core was modeled as a 19 × 19 lattice. The size of each lattice is 12.7279 cm × 12.7279 cm, so the diagonal of the lattice is 18, which is a suitable step size for fuel rods. The extracted figures from the output of MCNP-4C are shown in Fig. 1. The β_{eff} in the HWZPR is calculated using the prompt method, which requires the calculation of the effective multiplication factor for total neutron and prompt neutron, separately. The input files including 500 cycles with 40,000 histories per cycle, were run as a KCODE source problem for critical calculation. The required

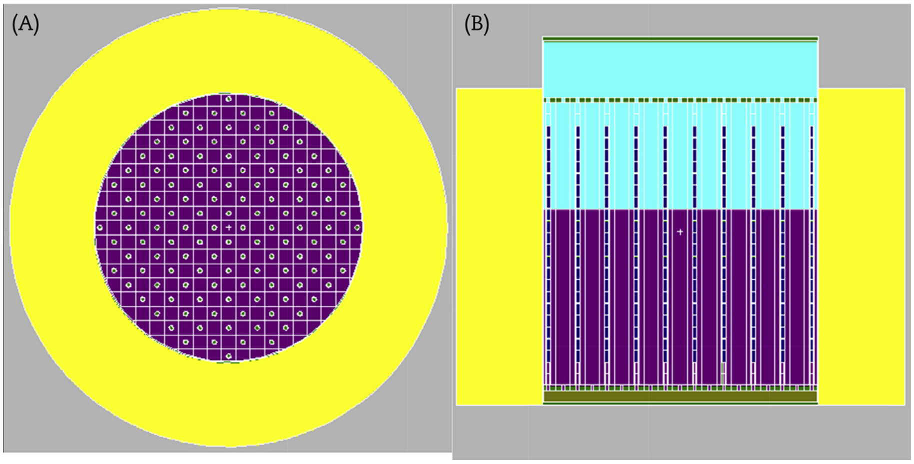

Fig. 1 – (A) Horizontal and (B) vertical view of simulated heavy water zero power reactor (HWZPR) by Monte Carlo N-Particle (MCNP).

value of the effective multiplication factor, k_{eff}, taking both prompt and delayed neutrons into account, was acquired in the straight calculation mode of MCNP4C calculation, using the data card KCODE. In the KCODE mode, the mean values of both prompt and delayed neutrons are used in criticality calculations. To prevent the influence of the delayed neutrons, a TOTNU data card with entry NO had to be used, to obtain the value of the effective multiplication factor for prompt neutrons, k_p. A TOTNU card with NO as the entry causes ν_p to be used, and consequently k_p to be calculated, for all fissionable nuclides for which prompt values are available. If the TOTNU card is used without any entry after it, the total average numbers of neutrons from fission ν, both prompt and delayed neutrons are used, and the total effective multiplication factor is calculated [4].

4. Noise analysis measurement

The horizontal view of the HWZPR is shown in Fig. 2. The He^3 detector is placed in a suitable position on the measurement guide tube in the core. The signals of neutron pulses detected by the He^3 neutron detector are amplified by the preamplifier, and then sent to the main amplifier for further amplification. After being discriminated and shaped, the pulses are sent to the statistical experiment control circuit and multifunction multichannel analyzer (MCA). The maximum channel number is 4,000, the channel width changed from 10 μseconds to 10^5 μseconds and the dead time between channels is 2.5 μseconds. The suitable working mode of the multi analyzer is chosen to do the different experiments. The schematic of the statistical experiment instruments is shown in Fig. 3 [5].

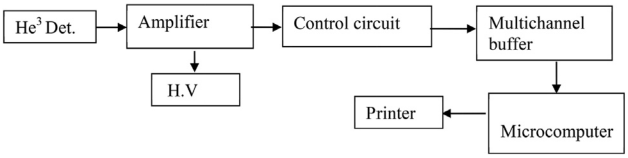

Fig. 3 – Schematic block diagram of the experimental setup. Det., detector; H.V, high voltage.

In the statistical experiment, an important physical parameter to be obtained is the prompt neutron decay constant $\alpha = \frac{\beta_{eff} - \rho}{\Lambda}$, where Λ is the mean neutron generation time and $\rho = \frac{k_{eff} - 1}{k_{eff}}$ is the reactivity. In delayed critical condition, $\rho = 0$ and the prompt neutron decay constant, denoted by α_0, is equal to $\frac{\beta_{eff}}{\Lambda}$. According to the HWZPR safety analysis report, the value of Λ is reported as 0.884×10^{-3} seconds.

4.1. *VTM ratio method*

The Feynman technique relates dynamic parameters to the ratio of the variance to the mean of the number of neutron counts collected in a fixed time interval. If we repeatedly measure the number of counts occurring in a given time interval in the nuclear system, we can relate the parameters to the VTM ratio of the number of counts:

$$\frac{\overline{S^2}}{\overline{C}} = \frac{\overline{C^2} - \overline{C}^2}{\overline{C}} \tag{3}$$

where C, $\overline{C}$, and $\overline{S^2}$ represent the number of neutron counts, the average of neutron counts, and variance of the counts in the fixed time interval, respectively.

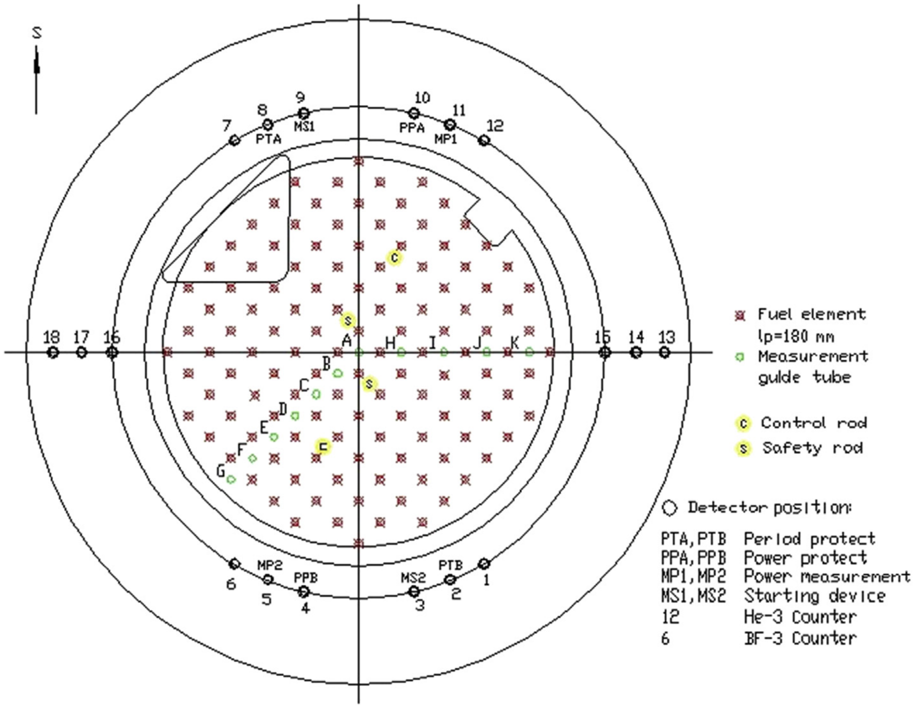

Fig. 2 – Horizontal view of the heavy water zero power reactor (HWZPR) core configuration (lattice pitch, 18 cm).

Regarding the Poisson distribution, $\overline{S^2} = \overline{C}$, therefore the VTM ratio is $\frac{\overline{C^2} - \overline{C}^2}{\overline{C}} = 1$.

For the reactor system, in addition to the neutrons which obey the Poisson distribution, there are correlative neutrons in the reactor, which makes the VTM ratio deviate from one. The degree of deviation from one is expressed by Y, then:

$$\frac{\overline{S^2}}{\overline{C}} = \frac{\overline{C^2} - \overline{C}^2}{\overline{C}} = 1 + Y \tag{4}$$

Y can be expressed as:

$$Y = \frac{\varepsilon D_v}{\rho_p^2}\left(1 - \frac{1 - e^{-\alpha\tau}}{\alpha\tau}\right) \tag{5}$$

where $\rho_p = \frac{k_p - 1}{k_p}$ is the prompt reactivity, ε is the detector efficiency, $D_v = \frac{\overline{v}^2 - \overline{v}}{\overline{v}^2}$ is the Devin factor, and τ is the measuring time interval. The method of the VTM ratio involves the measurement of Y, and usually Y values corresponding to different τ values. Finally, the least square fitting technique is performed to obtain α and $\varepsilon D_v \big/ \rho_p^2$.

In this experiment, the important task is to collect data, which are difficult to deal with and easily cause mistakes if the process is performed offline. In order to save the data process time, the working mode of the multi analyzer is chosen in such a way that the neutron pulses from the detector will be the input signals of the channel and the clock pulses will be the storing signals. The channel is the neutron pulse number recorded in timeτ, while the stored number at this channel, N_i, represents the number of intervals during which i pulses are collected. Therefore, the mean value and the mean square value can be easily written as:

$$\overline{C} = \frac{\sum_{i=1}^{m} iN_i}{\sum_{i=0}^{m} N_i} = \frac{1}{G}\sum_{i=1}^{m} iN_i \tag{6}$$

$$\overline{C^2} = \frac{\sum_{i=1}^{m} i^2 N_i}{\sum_{i=0}^{m} N_i} = \frac{1}{G}\sum_{i=1}^{m} i^2 N_i \tag{7}$$

where m represents the maximum number of channels where neutrons are recorded, N_i is the counts in i-th channel, i.e., number of the intervals during which i neutrons are entered, and G is the total cycle number. From the mentioned equations, one can get:

$$\frac{G\sum_{i=1}^{m} i^2 N_i - \left(\sum_{i=S_k}^{L_k} iN_i\right)^2}{G\sum_{i=S_k}^{L_k} iN_i} - 1 = Y_i = A\left(1 - \frac{1 - e^{-\alpha t_j}}{\alpha t_j}\right) \tag{8}$$

where S_k is the minimum count at time interval t_j and L_k is the maximum count at time interval t_j. At the same subcritical condition, the variance mean value ratios can be obtained for different time intervals. The relationship curve of Y_i and t_i can thus be obtained and will be processed by the least square fitting method. The A andα can then be obtained [6].

4.2. *EPS method*

In the Rossi-alpha procedure for measurements, a multichannel analyzer is used as a multiscaler; the first pulse starts the analyzer and subsequent pulses are recorded in the appropriate channel. No interest is attributed to whether the neutron density is increasing, decreasing, or remaining constant. The endogenous pulse technique uses a triggering pulse that occurs when the fluctuating neutron density reaches a preselected level above the mean value. The natural fluctuation of the reactor will produce spontaneous bursts in the form of pulses which are significantly higher than the mean level and may be considered to be due to variations in the fission rate. The decay of these pulses to a lower level is characterized by the fundamental decay constant (α). The improvement of this technique over the conventional Rossi-alpha measurements is due to the preselection of measuring periods when the neutron density is decaying. This provides an increased signal to background ratio, because only decay chains of significant amplitude are analyzed. Such a technique has some of the features of a pulsed neutron measurement while retaining the simplicity, economy, and convenience of the conventional Rossi-alpha measurements. The reduction in time required over a conventional Rossi-alpha measurement is such that it is practical to carry out EPS measurements on thermal reactors. The experimental setup is substantially the same as that used for the Rossi-alpha experiment, except that a special preselection and triggering device is used. When a reactor is operated at critical or slightly subcritical state, the natural fluctuation of the reactor will produce prompt paroxysmal pulses which are higher than the average level, and they will decay according to exponential law. The decay constant is the prompt neutron decay constant, α. If these pulses are used to trigger the multichannel time analyzer, and the latter is operated under the multichannel scaling mode, after the neutron decay has been recorded, we can obtainα. The endogenous pulsed technique is similar to that of the pulse neutron source experiment, but the pulses are produced from the natural fluctuation of the neutrons in the reactor. The neutron number variation with time is similar for both methods:

$$n(t) = n_0 \exp(-\alpha t) + \overline{n} \tag{9}$$

where $\overline{n}$ is the mean neutron count or the mean background count and n_0 is the pulse neutron count of the starting channel. The mean neutron count at interval $\varDelta t$ is:

$$\begin{aligned} &\overline{n} = F\varepsilon\varDelta t \quad \text{For critical} \\ &\overline{n} = S_0\varepsilon\varDelta t/\overline{v}(1 - k_{eff}) \quad \text{For subcritical with an external source} \end{aligned} \tag{10}$$

where F is the fission rate, ε is the efficiency of the detector, S_0 is the intensity of external source, $\overline{v}$ is mean number of neutrons per fission, and k_{eff} is the effective multiplication factor. The above equation can be simplified as:

$$n'(t) = n_0 \exp(-\alpha t) \tag{11}$$

where $n'(t) = n(t) - \overline{n}$ and $\overline{n}$ is the background of the decay curve of neutrons in the reactor. Usually $\overline{n}$ is taken from the average value of the counts of the last channels of the decay curve. The experimental data are fitted with an exponential function to obtain the value of α according to Eq. (11).

The measuring time interval is relatively long and is adjusted in such a way that the ratio of signal to background is suitable. The tests are required to choose the ratio of signal to

Table 1 – Results of Y parameter for different τ and water levels in the variance to mean (VTM) method.

τ(sec)	H_{eff} (mm)				
	1,560.2	1,568.1	1,576.0	1,584.7	1,592.5
5e-3	0.386	0.433	0.456	0.463	0.526
0.01	0.768	0.703	0.801	0.864	0.999
0.02	1.312	1.363	1.554	1.771	1.864
0.04	2.260	2.470	2.704	3.016	3.323
0.06	2.997	3.350	3.742	4.027	4.464
0.08	3.664	4.110	5.584	5.053	5.654
0.1	4.025	4.401	5.043	5.825	6.645

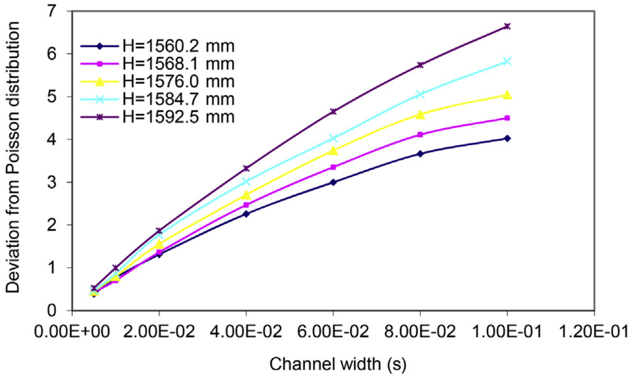

Fig. 4 – Variation of Y deviation of Poisson distribution versus channel width.

background such that the measuring time can be shortened and results with relatively high accuracy can be obtained.

In this experiment, when the number of collected neutron pulses in a given time interval reaches the preset value, the measuring system is triggered. Since the heavy water natural uranium reactor is a system with high background and low fluctuation, in the control circuit, besides the preselector, is a background deduction circuit that increases the signal to background ratio. After passing through the background deduction circuit, the neutron pulses are sent to the preselector, the output of which will trigger the multichannel analyzer to begin the cycling counting [6].

5. Results and discussion

5.1. *Calculation results*

The first calculation in KCODE mode (500 cycles with 40,000 histories per cycle) with TOTNU card and NO, provided the following value of effective multiplication factor for only prompt neutrons: $k_p = 0.9976 \pm 0.00013$. The second calculation result was the value of total effective multiplication factor: $k = 1.00522 \pm 0.00013$.

Table 3 – Results of $\bar{n}$ and α parameters for different water levels in the endogenous pulse source (EPS) method.

Water level (mm)	1,576.2	1,584.6	1,599.5
$\bar{n}$ (count/sec)	4,580± 1.5	5,981 ± 1.3	11,252 ± 1
α (sec^{-1})	18.99 ± 2.6	14.88 ± 3.3	11.97 ± 4.6

Data errors are presented as %.

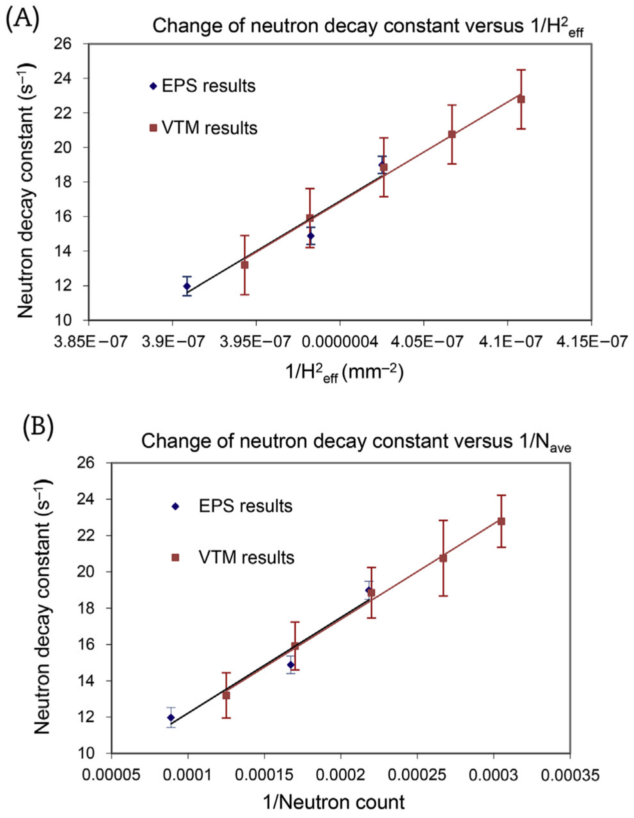

Fig. 5 – Variation of measured neutron decay constant in different water level in the heavy water zero power reactor (HWZPR). (A) Versus $1/H^2_{eff}$. (B) Versus $1/N_{ave}$.

The effective delayed neutron fraction for the HWZPR reactor, calculated using the prompt method, is:

$$\beta_{eff} \cong 1 - \frac{k_p}{k} = 1 - \frac{0.9976}{1.00522} = 0.007580 \pm 3.4\% \qquad (12)$$

5.2. *Experimental results*

In the VTM and EPS experiments, the proportional counter He^{3}was used to measure the neutron decay constant (α) at different water levels. In order to do the noise analysis

Table 2 – Results of A and α parameters for different water levels in the variance to mean (VTM) method.

Water level (mm)	1,560.2	1,568.1	1,576.0	1,584.7	1,592.5
A	6.67 ± 3.75	7.77 ± 6.5	9.28 ± 4.7	11.59 ± 5.6	14.82 ± 6.87
α (sec^{-1})	22.78 ± 6.3	20.75 ± 10	18.85 ± 7.4	15.91 ± 8.3	13.19 ± 9.5

Data errors are presented as %.

Table 4 – The results of α_0 and β_{eff} by different methods.

Methods	VTM		EPS		MCNP result
Parameter	$\alpha_0(\text{sec}^{-1})$	β_{eff}	$\alpha_0(\text{sec}^{-1})$	β_{eff}	β_{eff}
$1/\overline{n}$	8.799	7.779–3	8.959	7.920e-3	7.580e-3 ± 3.4%
$1/H_{eff}^2$	8.800	7.780e-3	8.933	7.897–3	

EPS, endogenous pulse source; MCNP, Monte Carlo N-Particle; VTM, variance to mean.

experiments, a suitable electronic circuit is prepared (Fig. 3). The multichannel analyzer is capable of working in different modes in VTM and EPS experiments. In the VTM experiment, five different subcritical conditions are considered. In each water level, measurement is done in the different seven time intervals. The height of heavy water correspondence of the different subcritical states (H_{eff}) and time intervals (τ) are shown in Table 1. By analyzing the neutron count in each time interval τ_i, the deviation of VTM ratio from one (Y_i) are calculated, according to Eq. (8). The results are shown in Table 1. In each subcritical condition, the curve of Y_i versus τ_i is plotted in Fig. 4. The curves are fitted by Eq. (5) and the decay constant (α) in five different subcritical levels are calculated. The results are reported in Table 2.

In the EPS method, the experiment is done in three different heavy water levels. The suitable mode of MCA is chosen, and the collected experimental data is fitted by Eq. (11) and the parameter α is calculated. The results are shown in Table 3.

5.3. *Calculation of neutron decay constant at delay critical condition (α_0)*

For both VTM ratios and EPS methods, the α values are obtained for the different water levels. By drawing the curve α verses $\frac{1}{H_{eff}^2}$, where H_{eff} is the height of the heavy water in the core, a straight line is obtained as.

$$\alpha = \frac{A}{H_{eff}^2} + B \tag{13}$$

The plot is shown in Fig. 5A. By the least square fitting method, the constant values A and B in Eq. (13) can be obtained. The measured critical water level is equal to 161.62 cm. So if the value of the critical water level is substituted in Eq. (13), the neutron decay constantα_0 can be calculated.

Additionally, by drawing the curve α verses $\frac{1}{\overline{n}}$, where $\overline{n}$ is the average counting rate of neutrons in the reactor, and interpolating the result to $\frac{1}{\overline{n}} \to 0$, the value α, related to delay critical condition, is obtained. The results in Fig. 5B are fitted by Eq. (14), and the constant b and α_0 are calculated:

$$\alpha = \alpha_0 + \frac{b}{\overline{n}} \tag{14}$$

In the delay critical condition $\rho = 0$, therefore.

$$\alpha_0 = \frac{\beta_{eff}}{\Lambda} \Rightarrow \beta_{eff} = \Lambda\alpha_0 \Rightarrow \beta_{eff} = 0.884 \times 10^{-3}\alpha_0 \tag{15}$$

The value of mean neutron generation time Λ is reported in the safety analysis report of the HWZPR. The experimental results for α_0 and β_{eff} are given in Table 4.

6. Conclusion

In this study, kinetic parameters in HWZPR are studied by noise analysis methods. For measuring the neutron decay constant (α), two different experiments including VTM ratio and EPS are setup. The neutron decay constant, α, is measured in different subcritical levels by the two mentioned methods. By interpolating the results, the neutron decay constant, α_0, in the delay critical condition is obtained. Then, the values α_0 and Λ are substituted in the Eq. $\alpha_0 = \frac{\beta_{eff}}{\Lambda}$, and the value of β_{eff} is drive. The average of measured α_0 and β_{eff} are equal to 8.87 (sec^{-1}) and 7.84×10^{-3}, respectively. Additionally, MCNP-4C code is used to calculate effective delay neutron fraction β_{eff} by the prompt method. The results are shown in Table 4. The difference between experimental and calculated β_{eff} is 3.4%. It should be noted that the good consistency between the calculated and measured result verifies β_{eff} calculation with MCNP-4C code. Since the HWZPR can be utilized in different core configurations, this calculation method can be used to predict β_{eff} in other lattice pitches. The calculation of kinetic parameters is necessary before any core configuration change.

Conflicts of interest

All authors have no conflicts of interest to declare.

REFERENCES

[1] Preliminary Safety Analysis Report on Heavy Water Zero Power Reactor, China Institute of Atomic Energy, 1992.
[2] S. Michalek, J. Hascik, G. Farkas, MCNP5 delayed neutron fraction calculation in training reactor VR-1, J. Electr. Eng. 59 (2008) 221–224.
[3] C.J. Werner, Determination of the Effective Delayed Neutron Fraction Using MCNP-4B, LA-UR- 99–629. CONF-990605, American Nuclear Society, Boston, 1999.
[4] J.F. Briesmeister, MCNP – A General Monte Carlo N-particle Trans-port Code, Version 4c, LA-13709-M, Los Alamos National Laboratory, Los Alamos, 2000.
[5] CIAE HWZPR project, Technical Transfer Document, HWR Neutron Statistics Experiment Technique and Data Processing, 1993.
[6] R.E. Uhrig, Random Noise Techniques in Nuclear Reactor Systems, Ronald press company, New York, 1970.