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Study about effective photoneutron coefficient in HWZPR

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ABSTRACT

In Heavy Water Zero Power Reactor (HWZPR), the photoneutron coefficient is a parameter of special significance for reactor safe operation and accurate measurement of the reactor power ascending period. Although, in the stable power operation, the fission delayed neutrons and the delayed photoneutrons are only the small fractions of the total neutrons in the reactor, but the certain time after the reactor shutdown they become the main neutron source. In order to measuring the effective photoneutron coefficient, the decay curve of the neutron intensity in the HWZPR was obtained as a function of time after shutdown. The experiment was repeated in the different reactor powers, lower than 40 W. The reactor was in the stable power for 40 min, before shutdown. By analyzing the decay curve into a sum of decreasing exponentials and using the theory of point kinetics, the effective photoneutron coefficient was measured. The delayed neutron and photoneutron counts were corrected to infinite irradiation time. According to the experimental results, the effective delay photoneutron coefficient is equal to 0.31. In continue, this parameter was calculated by MCNPX code. The comparison of the experimental and calculated results show that the relative difference between them is less than 4% and the MCNPX calculated results is verified.

1. Introduction

In the heavy water moderated reactor, delayed photoneutrons are produced in addition to delay neutrons. High energy gamma rays are emitted by fission products during their decaying. The delay photoneutron result from (γ,n) reactions in deuterium. The threshold energy of this reaction is equal to 2.23 MeV. For an actual reactor, not all γ rays with energy higher than 2.23 MeV might react with deuterium to produce photoneutrons. Some of them, will be absorbed in the fuel rod due to pair production reaction before entering the heavy water, some might either escape from the reactor or be absorbed by Compton reaction in the core structural materials after entering the heavy water. According to definition, the effective photoneutron coefficient ($\bar{\theta}$) is the fraction of the high energy γ rays which can effectively produce delayed photoneutrons. This parameter is the main subject to be discussed in this paper. Its value will mainly depend on the size of the fuel pellet. The smaller the size of the fuel pellet is, the larger the value $\bar{\theta}$ will be, but it is always less than 1.

In this research, the experimental method for measuring the effective photoneutron coefficient is presented. This parameter was measured in HWZPR with new lattice pitch 20 cm in different reactor powers. Beside of experimental procedure, this parameter was calculated by MCNPX. The experimental result not only compared with calculated result but also compared with corresponding value in original core lattice pitch 18 cm.

2. Theory of effective photoneutron coefficient

For a reactor without an external source, the changes of neutrons with time can be described with the point reactor kinetics equations:

$$\begin{cases} \frac{dn(t)}{dt} = \frac{\delta\rho - \bar{\gamma}\beta}{\Lambda} n(t) + \sum_i c_i(t)\lambda_i \\ \frac{dc_i(t)}{dt} = \frac{\bar{\gamma}\beta_i}{\Lambda} n(t) - c_i(t)\lambda_i \end{cases} \quad (1)$$

$$\bar{\gamma}\beta = \bar{\gamma}\sum_{i=1}^{6}\beta_i + \bar{\gamma}\sum_{i=7}^{15}\theta_i\beta_i \qquad i = 1,\ldots,15 \quad (2)$$

where θ_i is the effective photoneutron coefficient, for i = 1 to 6, $\theta_i = 1$.

We define $\bar{\theta} = \frac{\sum_{i=7}^{15}\theta_i\beta_i}{\sum_{i=7}^{15}\beta_i}$, then

$$\bar{\gamma}\beta = \bar{\gamma}\sum_{i=1}^{6}\beta_i + \bar{\gamma}\bar{\theta}\sum_{i=7}^{15}\beta_i \qquad i = 1,\ldots,15 \quad (3)$$

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The number i = 1,2,...,6 is the fission delayed neutrons groups and i = 7,8,...,15 is the photo induced delayed neutrons groups, n (t) is the neutron density in the reactor at time t, δρ is the prompt negative reactivity insertion for shutdown, Λ is the neutron generation time, $\bar{\gamma}$ is the mean effective coefficient of delayed neutrons, λ_i is the decay constant of delay neutrons group i, C_i is the concentration of the precursor of delayed neutrons group i, β_i is the fraction of delayed neutrons group i. The values of λ_i and β_i related to delayed and photo delayed neutrons in HWZPR are shown in Table 1 (China Institue of Atomic Energy, 1992).

When $\frac{\delta\rho-\bar{\gamma}\beta}{\Lambda}\rangle\rangle\lambda_i$, there exists the following approximate solution:

$$n(t) = \sum_{i=1}^{m} A_i e^{-\alpha_i t} \tag{4}$$

where: $A_i = n(0)\frac{\bar{\gamma}\bar{\theta}\beta_i}{\bar{\gamma}\beta-\delta\rho}F_i$, $a_i = \frac{\lambda_i}{1+\frac{\bar{\gamma}\bar{\theta}\beta_i}{\bar{\gamma}\beta-\delta\rho}}$, and $F_i = 1 - e^{-\lambda_i T_0}$.

F_i is the accumulation factor of the delayed neutrons. It is a modification to account for that the delayed neutrons for each group are not saturated in the time interval T_0. T_0 is the time interval of stable operation of the reactor, and n(0) is the reactor neutron density during the time interval T_0.

Substitute n(t) in Eq. (4) with the neutron decreasing curve measured after the reactor shutdown, i.e., the counts in each channel, $n(t_j)$, j = 1,2,..,N where j is the channel number of a multichannel analyzer, therefore we can get: $n(t_j) = \sum_{i=1}^{m} A_i e^{-\alpha_i t_j}$

During the reactor stable operation, the neutron density n(0) is difficult to be measured accurately in the experiment, so the time point t_s is selected as normalizing point which is usually chosen within the time interval from 30 to 60 s after the reactor shutdown. In the data processing, λ_i and β_i can be obtained directly from the delayed neutron parameters in the references and $\bar{\gamma}$ can be obtained from theoretical calculation, therefore $\bar{\theta}$ and $\delta\rho$ can be calculated from the least square fitting (Keepin, 1965; CIAE HWZPR, 1992).

3. Reactor description

HWZPR which is a critical assembly with maximum power of 100 W can be utilized in different lattice pitches 12.73, 14.14, 18 and 20 cm. In the original core, lattice pitch was equal to 18 cm. Based on the last change of core configuration, this was changed from 18 cm to 20 cm. HWZPR employs the metal natural uranium as fuel, heavy water as moderator and graphite as reflector. The reactor core is cylindrical and installed in an aluminum vessel with 2.4 m in diameters, 3 m high and 1 cm thickness. Outer surrounding of the vessel are 75 cm graphite reflector and 35 cm heavy water reflector at the bottom of the core. The height and diameter of 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. The height and diameter of the active core are 205.2 cm and 238 cm, respectively.

The fuel rods in core were arranged in square lattice with pitch equal to 20 cm, and different physical parameters including effective photoneutron coefficient were measured. The horizontal view of the HWZPR is shown in Fig. 1. In the experiment, the fission chamber detector was placed inside N1 guide tube in suitable position in the core and remained unchanged during the experiment. The signals of neutron pulses are detected by fission chamber neutron detector are amplified by the preamplifier, and then sent to the main amplifier for further amplification. The discriminated and shaped pulses are sent to multichannel scaler and microcomputer system for data processing (China Institue of Atomic Energy, 1992). The schematic of the measuring system is shown in Fig. 2.

Table 1
Delayed and photo delayed neutron parameters.

Group No.	λ_i(sec^{-1})	Real fraction β_i
1	0.0124	0.21450E−3
2	0.0305	0.14235E−2
3	0.111	0.12740E−2
4	0.301	0.25675E−2
5	1.14	0.74750E−2
6	3.01	0.27300E−2
7	6.27E−7	0.41600E−6
8	3.63E−6	0.10430E−5
9	4.38E−5	0.32960E−5
10	1.17E−4	0.23680E−4
11	4.28E−4	0.20992E−4
12	1.50E−3	0.34176E−4
13	4.81E−3	0.71040E−4
14	1.69E−2	0.20736E−3
15	0.2772	0.65984E−3

4. Principles of experiment

In the experiment, the reactor is operated at a certain power level for some time to make the fission delayed and delayed photoneutrons basically saturated, then the large negative reactivity is promptly imposed on the reactor to measure the reactor power decreasing along with time. For the period of time not long after the reactor shutdown, the decay curve of the reactor neutron level basically depends on the parameter of the delayed neutrons, especially for the period after that, the delayed photoneutrons will play a significant role, the mean photoneutron efficiency can be obtained from analyzing this curve.The reactor is usually operated at certain power level for very long time to make all the delayed neutron accumulation saturated. Actually this is both impractical and unnecessary for a zero power reactor, in the mean photoneutron coefficient measurement. According to the formula, the delayed neutron accumulation factor is $F_i = 1 - e_0^{T}$. For the fission delayed neutrons, they get saturated quickly duo to their short half live that is $F_i = 1$. But for photo induced delayed neutron, it would take quite a long time to be saturated due to their long half- hives. Fortunately the fractions of these long half live delayed neutrons are small. The quantity $F = \sum_{i=7}^{15} F_i a_i$, is the delayed photoneutron fraction weighted accumulation factor, where $a_i = \frac{\beta_i}{\sum_{i=7}^{15}\beta_i}$. The relation between the photoneutron accumulation factor F and the stable power operation T_0 shows that, the stable power operation time, between 30 and 40 min is enough.

In the experiments there are no special requirements for the reactor power level. Generally the measured neutron decreasing curve (count in each channel) should meet the statistical error requirements. On the other hand, the count rates should not be too high to cause serious problem of count losing. Usually the fission chamber is inserted somewhere in the reactor, then the reactor power level is adjusted to make the neutron count loss in each channel due to the dead time for the start part of the neutron decreasing curve around 5%, By this way the count rate in the later part of the neutron decreasing curve will not be too low. The above procedure was repeated several times until satisfactory results are obtained before the formal experiments.

In order to measure neutron decreasing curve accurately, the neutron pulse counts in each channel of the multichannel system, need to be modified for the background. The reactor neutron background is the subcritical count rate under the condition that there is no delayed neutron accumulation and the reactor state is entirely the same as the state with the prompt large negative reactivity insertion into the reactor. The reactor background must be