Original Article

Measurement of safety rods reactivity worth by advanced source jerk method in HWZPR

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A B S T R A C T

Accurate measurement of the reactivity worth of safety rods is very important for the safe reactor operation, in normal and emergency conditions. In this paper, the reactivity worth of safety rods in Heavy Water Zero Power Reactor (HWZPR) in the new lattice pitch is measured by advanced source jerk method. The average of the results related to two different detectors is equal to 29.88 mk. In order to verify the result, this parameter was compared to the previously measured value by subcritical to critical approach. Different experiment results are finally compared with corresponding calculated result. Difference between the average experimental and calculated results is equal to 2.2%.

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1. Introduction

The Heavy Water Zero Power Reactor (HWZPR) is a critical assembly with maximum power and thermal neutron flux equal to 100 Watts and 10^9 n/(cm^2.sec), respectively. Four different lattice pitches 12.73, 14.14, 18.00 and 20.00 cm are available in HWZPR. In order to study reactor physical parameters in different core configuration, the lattice pitch was changed from 18 cm to 20 cm. The result of first criticality experiment was reported, before [1]. Also, the effective photo-neutron coefficient in the new core configuration was measured and presented [2].

In accordance with the principle of diversity, two emergency shutdown systems were designed in HWZPR consisting of heavy water emergency draining system and safety rods dropping (scram) system. From the point of safety considerations, measurement of safety rods reactivity worth is very important. The source jerk method of subcritical reactivity measurement appears to have certain advantages over other methods. Therefore, in this study the negative reactivity worth of safety rods is measured in the new core by this method. In addition, the experiment results are compared with calculated result. The relative consistency shows that the

calculation method can be used to predict physical parameters in two other lattice pitches i.e. 12.73 and 14.14 cm before reactor operation.

2. Description of HWZPR safety rods

There are two safety rods among the fuel assemblies in the core. They are symmetric to the core center. Their positions do not change with the variation of the lattice pitch. The safety rod is made of Cd with the diameter of 52 mm. The effective length of the absorber is 2030 mm and the weight of the rod is 7.0 kg (Fig. 1).

The safety rods are cadmium absorbers which can be manually operated or automatically inserted into the core rapidly in emergency situation. According to the safety analysis report, the reactivity worth of two safety rods should be equal or higher than 2% Δk/k. The drop time of rods is less than 1.5 s. In this condition if the water level does not change, one safety rod can shut down the reactor. The characteristics of safety rod are shown in Table 1 [3].

3. Safety rods reactivity worth measurement

The horizontal view of the HWZPR is shown in Fig. 2. The position of safety rods are shown in this figure. He-3and BF$_3$detectorsare placed in the suitable positions in the Al guide tubes in the reflector and core, respectively. The pulse signals of neutron

Fig. 1. Vertical view of HWZPR safety rod (Dimensions are in mm).

Table 1
Characteristic of HWZPR safety rod.

Outer diameter of the cadmium absorber	44 mm
Inner diameter of the cadmium absorber	42 mm
Length of cadmium section	288 mm
Outer diameter of the absorber section	46 mm
Inner diameter of the absorber section	40 mm
Length of one absorber section	290 mm
Total length of the absorber in the safety rod	2030 mm
Outer diameter of the safety rod	52 mm
Total length of the safety rod	2336 mm
Total weight of the safety rod	7 kg
Distance between the lowest end surface of the cadmium ring and bottom of the safety rod	235 mm
Reactivity worth of each safety rod	>1% Δk/k

detectors are amplified by the preamplifier, and then sent to the main amplifier for further amplification. After discrimination and shaping, the pulses are sent to the related experiment control circuit and multifunction multichannel scaler (MCS). The

maximum channel number is 4000, the channel width range isbetween0.1–10^5 s and the dead time of the detector (including electronic system) is 2.5 μsec. For doing different experiments, suitable working mode of the MCS is selected. The schematic experimental set up is shown in Fig. 3 [4].

3.1. Advanced source jerk experiment

The advanced source jerk (source cut off) is devolved from conventional source jerk method. These two methods are the same in basic principle but different in the employed apparatus and data processing methods. In the conventional source jerk, a constant external source is placed in the subcritical reactor. Soon after the neutron count reaches a constant value, the external source shall be removed promptly. The negative reactivity of the reactor is determined on the basis of the stable neutron count before the source being removed and the neutron count changing versus time after the source being removed. Usually free dropping, pneumatic device, and other mechanical methods are used to remove the external source and hence the external source can hardly be removed instantaneously. With the development of pulsed neutron experiment, the pulsed neutron apparatus is used in the source jerk experiment. A neutron generator is placed at the suitable position under the reactor and can work as a neutron source under direct current mode or pulse mode. Then the neutron tube is stopped by command of the electron tube in the last stage of amplifier. In this case, the external neutron source is easily removed promptly. This way of removing neutron source is called advanced source jerk method.

In HWZPR because of the existence of photo neutrons, it takes impractically long time to reach stable neutron count. Fortunately, neutron stability is not required for the method introduced in this paper [4].

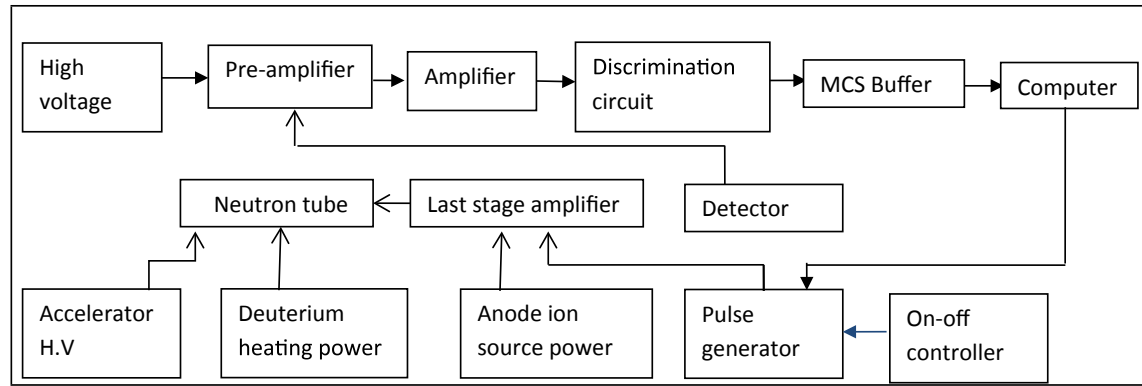**Fig. 2.** Horizontal view of HWZPR core configuration (New lattice pitch = 20 cm).

Fig. 3. Schematic block diagram of the ASJ experimental setup.

3.2. Theory

According to the point reactor theory, the kinetics equations of a bare homogeneous reactor are as follows:

$$\frac{dn(t)}{dt} = \frac{\rho - \beta}{\Lambda} n(t) + \sum_{i=1}^{15} \lambda_i C_i(t) + S(t) \tag{1}$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t) \qquad i = 1, \ldots, 15 \tag{2}$$

$$S(t) = \begin{cases} s_0 & 0 \leq t < t_1 \\ 0 & t_1 < t \end{cases} \tag{3}$$

Where $n(t)$ is the neutron count, ρ is negative reactivity at the sub-critical condition to be measured, λ_i is a decay constant of delayed neutrons in group i, $C_i(t)$ is the nuclear density of the precursor of the delayed neutrons in group i, β_i is the fraction of delayed neutrons in group i. In HWZPR, in addition to 6 delays neutron group due to fission fragments, because of interaction between gamma and deuteron, according to the half-life of precursors, 9 groups of delay photo neutron are also produced. Λ is the neutron generation time and S is the intensity of the neutron source.

With attention to above equations and boundary conditions, we have:

$$-\frac{\rho}{\beta} = \frac{\frac{\Lambda}{\beta} n(t_1) + \sum_{i=1}^{15} a_i e^{-\lambda_i t_1} \int_0^{t_1} n(t) e^{\lambda_i t} dt}{\int_0^{t_1} n(t) dt} \tag{4}$$

Where: $a_i = \frac{\beta_i}{\beta}$. and Λ, β and β_i parameters were calculated for HWZPR's new core configuration [5–8]. Therefore by measuring $n(t)$ in the experiment, the negative reactivity ρ can be determined from above equation.

3.3. Experimental procedure

In order to measuring reactivity worth of safety rods,

experiment is done in two steps. At the first step the reactor is adjusted to the sub-critical state about $K_{eff} = 0.996$ for measurement. At the moment t = 0, the MCS is started-up and the pulsed neutron source operates automatically and injects neutrons into the reactor at the same time. At the moment t = t_1 the pulsed neutron source stops working while the MCS continues working until the neutron count reaches to a value close to the background. In order to decrease statistical error of neutron count, in channel number 150 the width of channel increases from 1 to 10 s.

In the second step, the safety rods are inserted into the core and the experiment is repeated. The time interval t_1 in the first step (safety rods out) and the second step (safety rods in) of the experiment are equal to 70 and 100 s, respectively. The working conditions of neutron generator in two steps are given in Table 2. In these conditions the ratio of signal to background is enough and the effect of the source in the experiment is considerable.

The recorded data by MCS related to He-3 and BF$_3$ neutron detectors are transferred to the computer and saved. Fig. 4 shows neutron count versus time for two detectors. The sudden decrease in the curves is related to source cut-off time and the jump to channel width change from 1 to 10 s (in channel number 150). Then the data are analyzed by processing program and the negative reactivity is obtained (Table 3). The reactivity worth of safety rods was obtained by subtracting the result of two steps.

The reactivity worth of safety rods has been previously estimated based on the subcritical to critical approach by startup BF$_3$ neutron detector. In this experiment extrapolated line of 1/n (inverse of neutron count) versus h(water level) is finally obtained. In subcritical condition at $K_{eff} = 0.996$, the safety rods are inserted into the reactor and the neutron counts are recorded. This value is substituted in the extrapolated line and the new water level is calculated. The difference of the resulting value and the water level in the core gives Δh that is proportional to safety rods reactivity (Fig. 5). If Δh is multiplied by calculated reactivity worth of water, the reactivity worth of safety rods is obtained [9].
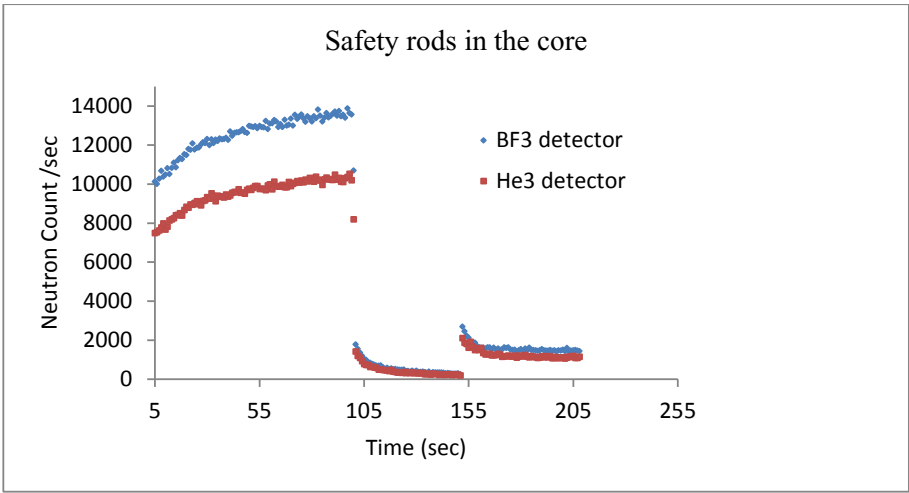
4. Result

In this study two neutron detectors are used in the experiments,

Table 2
Characteristic of pulsed neutron generator in ASJ experiment.

Safety rods position	Pulse width (msec)	Pulse period (msec)	Accelerator voltage (keV)	Anode voltage (keV)	Heater current (Amp)
out	0.9	1	90	2	1
in	0.9	1	110	2	1
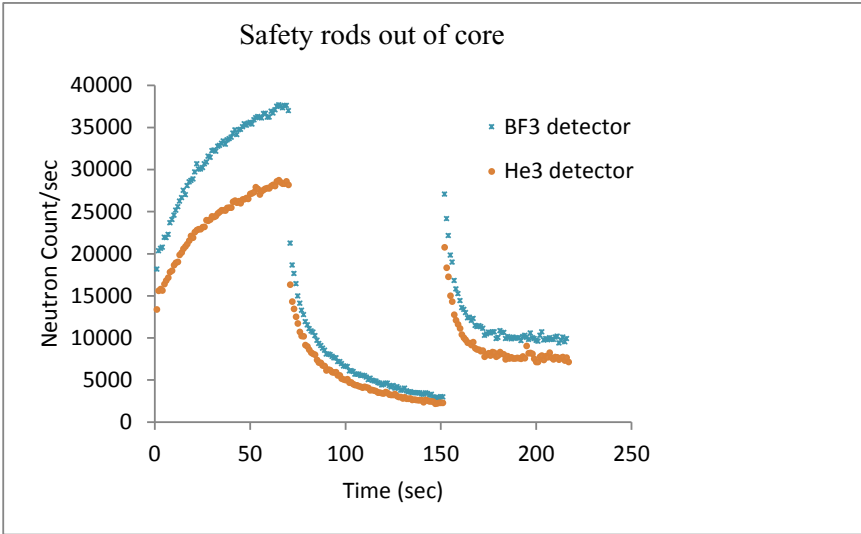
(a)

(b)

Fig. 4. Neutron count versus time (during source injection and after source removal) (a) Safety rods are out (b) safety rods are in.

Table 3
Results of background, maximum neutron count and reactivity in ASJ experiments.

Safety rods	Detector	Background/sec	Max. neutron count/sec	Reactivity ($)
out	He-3	739.5	28000	0.725
	BF$_3$	969.1	37000	0.753
in	He-3	118.8	10000	4.683
	BF$_3$	149.1	13500	4.764

separately. For measuring the reactivity worth of safety rods in the new core, the ASJ experiment setup is prepared. The negative reactivity is measured in two different subcritical conditions. At first the safety rods are out of the core and then they are inserted into the core. By subtracting the results, the reactivity worth of safety rods is obtained. As we know, due to shadowing effect, the reactivity worth of two safety rods is smaller than the sum of the

reactivity worth of safety rod 1 and 2. Therefore if reactivity worth of two safety rods is above 2%, certainly the each safety rod separately satisfies the requirement in Table 1. The average of BF$_3$ and He-3 results is considered as safety rods' reactivity worth. The value of β is equal to 0.0075 in HWZPR [2].Additionally, the result of subcritical to critical approach for measuring safety rods reactivity worth and calculated result are shown in Table 4, for comparison.
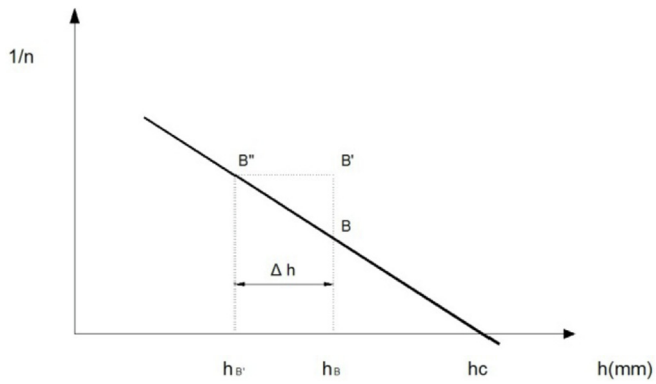
Fig. 5. Schematic view of subcritical to critical approach for measuring safety rods reactivity worth. (B is neutron count inverse when safety rods are out. B'&B'' are neutron count inverse when safety rods are in. Δh is heavy water levels difference. H$_c$ is critical water level.)

Table 4
Experimental and calculated results for reactivity worth of safety rods.

Normal experiment (Δk/k)	ASJ experiment (Δk/k)	Calculated results (Δk/k)
0.02992 ± 8.7%	0.02988 ± 5.9%	0.03057 ± 2%

Difference between ASJ experiment result and corresponding calculated parameter is equal to 2.2%.

5. Conclusion

In brief, negative reactivity can be accurately measured by ASJ method. In this paper the safety rods' reactivity worth is studied. The results show that the safety rods reactivity worth satisfies safety criteria. The consistency of the measured and calculated results shows the validation of calculation code and nuclear data. Procedure of calculation can be used to estimate safety rods reactivity in new core configurations with lattice pitches 12.73 and 14.14 cm in future. Only if safety criteria are satisfied, we have permission to change lattice pitch and operate the reactor in new core configuration.

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