AGN-201K Coarse Rod Worth Calibration by Neutron Source Multiplication Method

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1. Introduction

The AGN-201K, an educational and research reactor of Kyung Hee University, is a zero-power reactor licensed to operate to have a maximum thermal power of 10 W. This reactor is operated by four control rods. The coarse rod (CR) is the most significant rod in controlling the reactivity of the AGN-201K during operation, while the two safety rods (i.e., SR#1 and SR#2) must always be fully inserted during operation, as the fine rod (FR) has a small rod worth. However, the methods used in nuclear reactor experiments program have limitations in measuring the CR rod worth. In the Positive Period (PP) method, the control rod is inserted from a fully withdrawn critical state to insert positive reactivity, and the power increase is measured to determine the inserted reactivity. However, in the case of the AGN-201K, the excess reactivity is designed to be smaller than the CR's rod worth [1], meaning that full withdrawal of the CR does not maintain critical state. Meanwhile, in the Compensation Method, there is no compensating control rod to offset the reactivity inserted by the CR, making it impossible to measure the control rod worth.

Due to these limitations, reactivity measurement in a subcritical state is required for CR rod worth calibration. Previous study for measurement of the subcriticality using the Modified Neutron Source Multiplication (MNSM) method [2], but limitations in determining the reactivity at reference state. Additionally, noise analysis techniques have been used to measure subcriticality, but these measures only covered reactivity worth from 19 cm to 0 cm [3]. Therefore, this study aims to calibrate the CR rod worth using the Neutron Source Multiplication (NSM) method.

Recently, Kyung Hee University has established an AGN-201K benchmark problem based on various experimental data and literature [4] and developed the MCCARD [5] model. The benchmark has validated with experimental measurements of critical rod position, Fine Rod (FR) worth, and thermal neutron distribution. In this study, McCARD calculations were performed using the benchmark model, and the calculated CR reactivity was compared with the experimentally calibrated values.

2. AGN-201K

The AGN-201K is an educational and research reactor installed at Kyung Hee University, with a maximum thermal power of 10 W. To date, 127 experimental educational programs have been held, and a McCARD benchmark has been established based on the accumulated experimental data. Figure 1 presents a radial cross-section and the core configuration of the AGN-201K. The core consists of a cylindrical stack of 9 fuel discs, each constructed 19.5 wt% UO_2 uniformly mixed within a polyethylene matrix with a diameter of 12.8 cm.

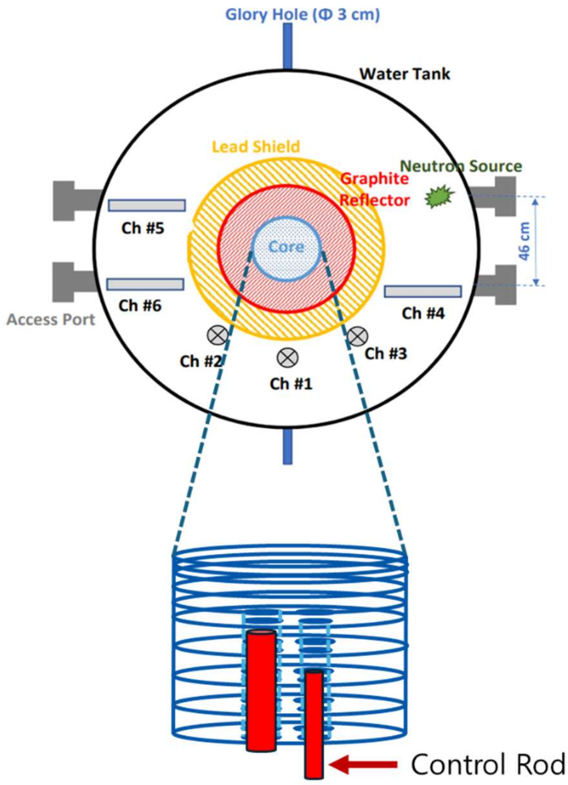

Fig. 1 AGN-201K cross-section and core configuration

The lower 4 fuel discs have 4 holes for control rod insertion. The AGN-201K controls reactivity using two SRs, a CR of the same size as the SRs, and a smaller FR. Each control rod is composed of fissile material, same as the fuel discs. As a result, different from commercial reactors, inserting the control rods introduces positive reactivity. Both SRs must be fully inserted during operation to ensure a shutdown margin, therefore the CR and FR can be inserted and intentionally controlled by the operator, after SRs insertion. Each control rod has a length of 16 cm and an insertion distance of approximately 23 to 24 cm. For the FR, which has a relatively small rod worth, the educational program includes calibration using the Positive Period Method and the Compensation Method. In this study, FR was withdrawn to reach the reactor at reference state, which is a subcritical steady state with known reactivity. Table I presents the calibrated integral rod worth of the FR. In the experiment, the total rod worth was calibrated as 212 pcm using the inhour equation, based on the reactor period measured by Ch#4. This result shows good agreement with the McCARD-calculated value of 221 ± 9 pcm, within the confidence interval.

Table I: Integral rod worth of FR calibrated by positive period method

Rod Position (cm)	Integral Rod Worth (pcm)
0	0
4	12
8	31
12	72
15	104
18	144
21	83
23	212

3. Method for Rod Worth Measurement

3.1. Neutron Source Multiplication Method

From the point kinetic equation, the number of neutrons at subcritical steady state by the source can be derive [6-7]. First, neutron balance in point kinetic equation as:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \lambda C + S = 0 \quad (1)$$

It should be noted that ρ is negative in the derivation. Next, the balance of the delayed-neutron precursor is:

$$\frac{dC}{dt} = \frac{\beta}{\Lambda} n - \lambda C = 0 \quad (2)$$

where:

n: Number of neutrons
ρ: Reactivity
β: Delayed-neutron fraction
Λ: Neutron Generation Time
λ: Decay Constant of precursor
S: Neutron Source Intensity

From the equation (2),

$$\lambda C = \frac{\beta}{\Lambda} n \quad (3)$$

Substituting (3) into equation (1),

$$n_0 = -\frac{\Lambda}{\rho} S \quad (4)$$

Through $k_{eff} = l/$ and $\rho = 1 - 1/k_{eff}$, equation (4) can be expressed as follows:

$$n = l(1-\rho)\frac{S}{-\rho} = \left(1 - \frac{1}{\rho}\right) lS \quad (5)$$

If the system is near the critical, l can be assumed constant. Therefore, rearranging equation (5) with respect to the constant,

$$lS = \frac{n_0}{\left(1 - \frac{1}{\rho_0}\right)} = \frac{n_i}{\left(1 - \frac{1}{\rho_i}\right)} = \text{Constant} \quad (6)$$

Based on this, expressing the desired ρ_i in terms of the known n_0, ρ_0, and the measurable n_1,

$$\rho_i = \frac{1}{1 - \frac{n_i}{n_0}\left(1 - \frac{1}{\rho_0}\right)} \quad (7)$$

Through this, the i-th reactivity (ρ_i) can be determined.

3.2 Positive Period Method

The Positive Period Method calibrates reactivity using the inhour equation based on the measured positive period from the increase in reactor power.

$$\rho(t) = \frac{\omega l_p}{1 + \omega l_p} + \frac{\omega}{1 + \omega l_p} \sum_{i=1}^{6} \frac{\beta_i}{\omega + \lambda_i} \quad (8)$$

where:

ω: Inverse period of reactor
l_p: Prompt neutron lifetime

In this study, kinetic parameters were calculated based on the AGN-201K McCARD benchmark modeling [8] and are shown in Table II.

Table II: Kinetic parameter of AGN-201K

Group	$\lambda_i (s^{-1})$	β_i
1	0.0133	0.00026
2	0.0327	0.00138
3	0.1208	0.00132
4	0.3028	0.00291
5	0.8496	0.00120
6	2.8535	0.00050
Sum	8.42E-02	0.00757
l_p(s)		2.10E-04

4. CR Worth Calibration by Neutron Source Multiplication Method and Positive Period Method

4.1. Experimental Method

This experiment was conducted through the following process. First, the critical rod position was searched. The

AGN-201K has a negative isothermal temperature coefficient, its temperature is determined by the experiment environment. Therefore, the critical rod position must be identified for each experiment. For using the FR worth at table I without interpolation, and the FR position was fixed at 18.00 cm to allow for sufficient negative reactivity insertion upon withdrawal. As a result, the critical CR position was measured to be 20.85 cm.

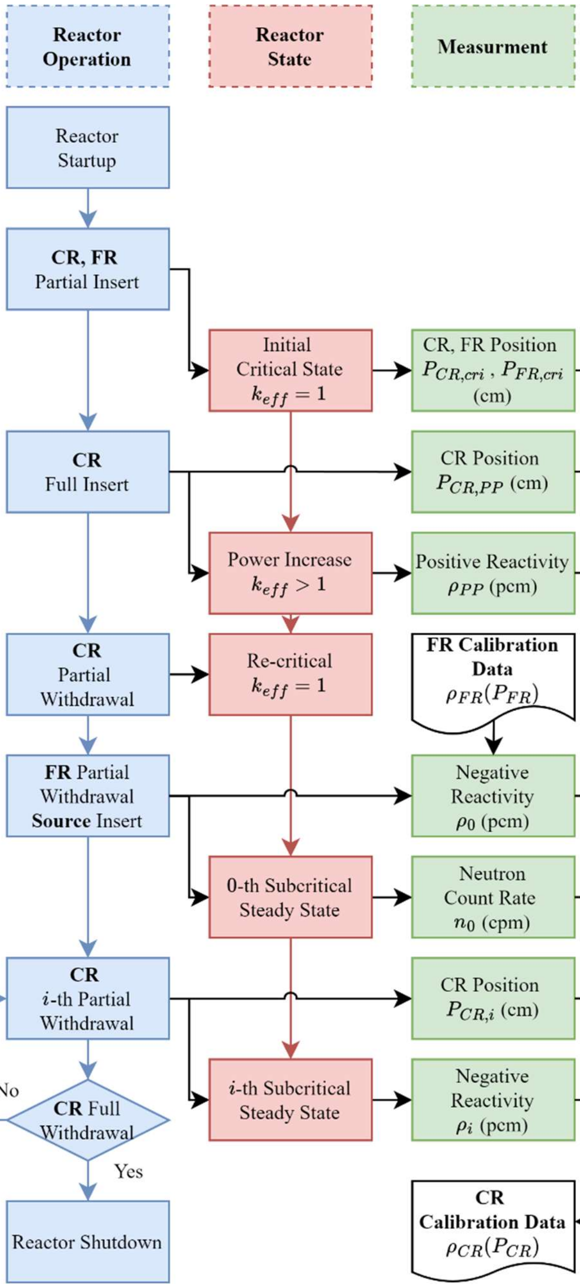

Fig. 2. Flow Chart of the NSM Experiment for Coarse Rod Worth Measurements in AGN-201K reactor

Next, the positive reactivity was measured using the positive period method by inserting only the CR to the maximum insertion position of 23.53 cm. After measuring the positive reactivity, the process moves back to the critical position, and the FR, which rod worth is known, is withdrawn to 12.00 cm. Then, when the insertion neutron source is inserted, a subcritical steady state with known reactivity (ρ_0) called as the reference state is reached, and the number of neutrons at this step is measured (n_0). After that, the CR is withdrawn little by little, and the number of neutrons is measured (n_i), so the reactivity (ρ_i) can be calculated using equation (7). Figure 2 visualizes this experimental process. In addition, the experimental step applied is as shown in Table III.

Table III: Reactor operation step and control rod position

Step	Control Rod Position (cm)	
	Coarse Rod	Fine Rod
PP*	23.53	18.00
CRI**	20.85	18.00
0	20.85	12.00
1	20.00	12.00
2	19.00	12.00
3	17.00	12.00
4	14.00	12.00
5	11.00	12.00
6	8.00	12.00
7	4.00	12.00
8	0.00	12.00

* Fully inserted rod position for positive period method
** Critical rod position

4.2. Experimental Results

Table IV and figure 3 presents the reactivity corresponding to various rod positions and the total rod worth measured in this study. It includes positive reactivity obtained using the Positive Period Method and negative reactivity determined using the NSM method. These experimental results are compared with the McCARD calculation results.

Table IV: Measured reactivity and propagated uncertainty by operation step

Step	Reactivity (pcm)		
	McCARD	Ch#1	Ch#5
PP	146 ± 6	166	
CRI	0	0	
0	-76 ± 6	-72	
1	-127 ± 6	-122 ± 0	-127 ± 1
2	-196 ± 6	-181 ± 1	-192 ± 3
3	-319 ± 6	-295 ± 1	-312 ± 5
4	-512 ± 6	-447 ± 2	-479 ± 6
5	-674 ± 6	-581 ± 3	-637 ± 8
6	-827 ± 6	-702 ± 3	-774 ± 10
7	-952 ± 6	-797 ± 4	-858 ± 13
8	-1034 ± 6	-848 ± 5	-947 ± 13
CR Worth	1114	941	1040

In the McCARD calculation, reactivities at the given rod positions were calculated using the AGN-201K benchmark model. Each calculation tracked 1,000,000 histories per cycle, with 200 inactive cycles for fission source convergence and 1,000 active cycles for reactivity calibration. At the critical rod position, the reactivity was calculated as 0.99929 ± 0.00002, which is consistent within the confidence interval, considering that the standard deviation of the benchmark is 47 pcm. In this study, the reactivities at each experimental step were calculated as relative reactivities with reference to the reactivity at the critical rod position. By using relative reactivity, uncertainty propagation was considered, resulting in an uncertainty of 3 pcm in the reactivity at each measurement point.

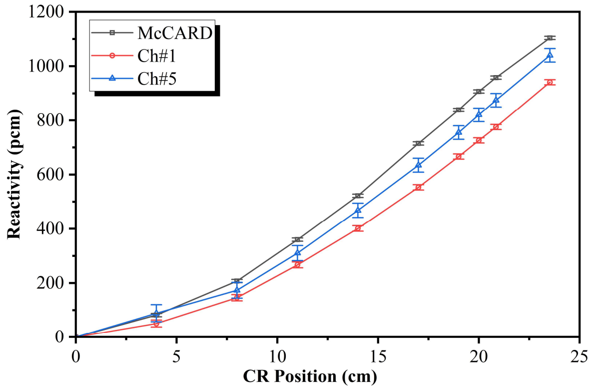

Fig. 3. Calibrated integral CR worth curve of AGN-201K

The CR worth from 20.85cm to 23.53cm, was calibrated using the inhour equation based on the positive period measured by Ch#4. In the reactivity calculation, data from the first 60 seconds after the control rod operation was excluded to account for the prompt jump effect. The measured reactor period was 25.7 seconds, and the reactivity was evaluated as 166 pcm.

For the CR worth calculation from 0.00 cm to 20.85 cm using the NSM method, ρ_i was determined based on the measured n_0 and n_i at each step. To obtain a true count rate (m) from the observed count rate (n), the detector dead time must be considered. Since Ch#1 is a BF_3 detector and Ch#5 is a He^3 detector, their dead times were assumed as 20μs and 14.5μs, respectively. The true count rate, considering the dead time (τ), is calculated as follows:

$$m = \frac{n}{1 - \tau n} \tag{9}$$

The uncertainty in count rates is calculated as follows:

$$\sigma_{n_i} = \sqrt{\frac{n_i}{T_i}} \tag{10}$$

Furthermore, the uncertainty in ρ_i, calculated from n_0 and n_i, is evaluated as follows:

$$\sigma_{\rho_i} = \sqrt{\sigma_{n_0}^2 \left(\frac{\partial \rho}{\partial n_0}\right)^2 + \sigma_{n_i}^2 \left(\frac{\partial \rho}{\partial n_i}\right)^2} \tag{11}$$

Based on the experimental results, the CR worth ($\Delta\rho_{CR}$) was calculated as follows:

$$\Delta\rho_{CR} = \rho_{PP} - \rho_8 + \rho_0 \tag{12}$$

where the ρ_{PP} is positive reactivity measured using positive period method, the ρ_0 is reactivity at reference state estimated by FR worth table. ρ_8 is reactivity measured using NSM method at experiment step 8, that CR was fully withdrawal.

In the case of McCARD, the control rod value was calculated by calculating the reactivity when the CR position was 23.53 cm and 0.00 cm while the FR position was fixed at 18 cm. In the comparison with McCARD, the reactivity at Step 8, which had the lowest criticality, was evaluated as 186 pcm higher for Ch#1 and 89 pcm higher for Ch#5 than -1034 pcm for McCARD. In addition, in the case of the control rod worth, Ch#1 was evaluated as -93 pcm and Ch#5 was evaluated as -76 pcm lower than 1114 pcm for McCARD. These results were in good agreement, considering that the calculations were made using the NSM method without any computational correction.

5. Conclusion

In this study, the individual and whole CR worth of the AGN-201K reactor was measured for the first time at the subcritical state using the NSM method. Considering the dead time for Ch#1 and Ch#5, the CR worth was measured as 941 pcm and 1038 pcm, respectively. Compared to the CR worth of 1114 pcm calculated by the McCARD MC code, it was confirmed that the experimental worth measured using the NSM method showed good agreement. Meanwhile, background count rates were not explicitly considered in this study because they were expected to be negligible. In the near future, the background effect will be addressed and the MNSM method will be applied for the CR worth measurement.

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