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Approach to Criticality and Control Rod Worth Calculations by McCARD with Improved AGN-201K Educational and Research Reactor Benchmark Model

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1. Introduction

AGN-201K [1] is a low-enriched uranium dioxide and polyethylene homogeneous fueled zero-power reactor surrounded by graphite moderator blocks and reflected by lead blocks and a water tank. The core of the AGN-201K is composed of nine fuel disks with a radius of about 25.8 cm, while the height and composition of each disc vary in detail. For safety and reactivity control, the AGN-201K is equipped with two safety rods (i.e., SR#1, SR#2) and two control rods (i.e., CR, FR), which are composed of the same material as its fuel.

After the installation of the AGN-201K nuclear reactor at Kyung Hee University (KHU) in 1982, numerous nuclear reactor experiments for education and research have been conducted. However, because sufficient measured data for the specifications have not been adequately obtained, detailed information was not readily available to simulate a comprehensive benchmark model for AGN-201K. In the previous study [2], we presented a new preliminary benchmark problem for AGN-201K, integrating data from publicly available reports, articles, and actual measurements [3,4,5].

In this study, an improved AGN-201K benchmark model was developed to satisfy various measured results for criticality, critical mass, and control rod worth.

2. Improvement of AGN-201K Benchmark Model

2.1 Improved AGN-201K Benchmark Model (M11)

In the previous study [2], the specifications for the structure and material compositions in the AGN-201K core were approximated due to unclear and unspecified input data. In this study, we have supplemented the approximated parts of the previous model (*M10*) with data from various documents and comprehensive experimental results. The AGN-201K reactor is equipped with a thermal fuse serving as the reactor safety shutdown mechanism. The thermal fuse connects the upper fuel disks with the lower fuel disks, and due to its lower melting point compared to fuel, it ensures the separation of the upper and lower fuel disks when the temperature abnormally rises, thus guaranteeing a subcritical state. In the improved model(*M11*), the thermal fuse and the space for the fuel disk to descend are added. In the AGN-201K, a thermal column is located on the top lead shielding to conduct experiments involving thermalized neutrons, such as neutron radiography. In the thermal column zone, graphite blocks are positioned during normal operation. They can be replaced with a water tank to confirm attenuation effects depending on the reflector material. In the previous model (*M10*), a water tank was placed in the thermal column, but in the improved model (*M11*), graphite blocks are simulated to be positioned correctly. For various proposes, 7 monitoring channels are located in the AGN-201K reactor. Among them, 3 channel detectors are located within the water shielding tank, whereas 4 channel detectors are located in the 4 access ports. A radon-beryllium neutron source is inserted into the access port for starting the reactor. In the improved model, the tally regions for the 5 detectors and the neutron source are considered for various reactor physics experiments. Figure 1 compares the previous AGN-201K benchmark model with the improved model.

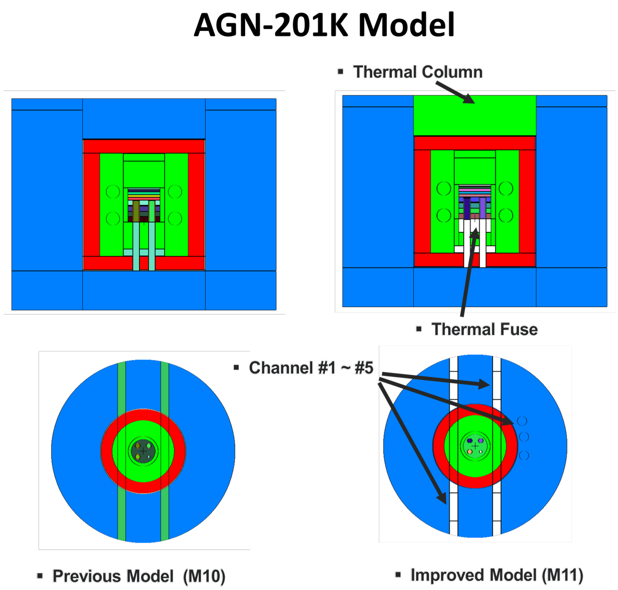

Fig. 1. Comparison between the previous and improved AGN-201K benchmark model

2.2 Criticality

Firstly, to examine the improved benchmark model, the criticality was calculated by the McCARD Monte Carlo (MC) code [6] with ENDF/B-VII.1 evaluated nuclear data library at various critical states corresponding to different control rod positions and temperatures. Table I shows the positions of CR and FR rods and the reactor temperatures based on a total of 22 experimental data points. Eighteen of these data points were obtained from the previous study [2], and four data points, highlighted in yellow were added from new experiments.

Table I: Positions of CR and FR rod at the critical state

ID		Control Rod Position (cm)*		
Problem	Exp.	CR (cm)	FR (cm)	Temp.
CRI001	T86-1	19.96	20.00	19.8
CRI002	T94-1	20.81	15.00	19.2
CRI003	T94-2	19.83	20.00	19.2
CRI004	T95-1	20.65	13.92	20.2
CRI005	T95-2	20.53	16.68	20.2
CRI006	T111-1	20.51	23.00	19.9
CRI007	T111-2	21.37	19.00	19.9
CRI008	T99-1	19.9	22.87	17.9
CRI009	T108-1	20.44	22.59	18.4
CRI010	T109-1	20.24	22.33	17.5
CRI011	T82-1	20.14	19.61	19.5
CRI012	T86-2	19.77	20.32	18.8
CRI013	T100-1	21.05	15.00	17.5
CRI014	T101-1	20.32	22.38	19.7
CRI015	T103-1	21.30	18.38	19.8
CRI016	T104-1	20.33	22.64	19.4
CRI017	T105-1	20.80	20.62	19.8
CRI018	T105-2	22.10	15.00	19.8
CRI019	T105-3	21.38	19.00	17.6
CRI020	T115-1	21.12	22.25	18.6
CRI021	T117-2	21.62	11.55	18.0
CRI022	T118-1	20.40	19.92	21.0

* Critical rod position is the distance from the bottom of the reactor core tank.

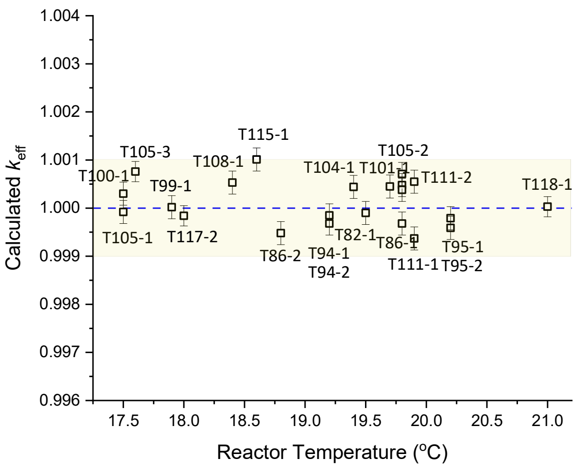

Fig. 2. Comparison of k_{eff} calculated by McCARD with the improved AGN-201K benchmark model at various critical state points

Figure 2 shows k_{eff} calculated by McCARD with the improved benchmark model. In the improved benchmark model, the average k_{eff} across the 22 criticality problems is at approximately 1.00013 with a standard deviation of around 47 pcm. In the previous model, the average k_{eff} was 0.99949. Overall, each k_{eff} value increased slightly, proportionally to the increase in the average value. As mentioned in the previous study, the primary sources of uncertainties in k_{eff} stem from the uncertainty of the control rod positions and the reactor temperature. Since the core temperature is controlled by an external air conditioner, it may not be uniform. Additionally, the uncertainty regarding the control rod positions at full insertion can also contribute to the errors.

3. Benchmarking of McCARD with the improved AGN-201K benchmark model

3.1 Approach to Criticality Approach (Critical Mass Estimation)

In general, the 'inverse multiplication ratio' technique is widely used to estimate the critical mass or critical control rod positions of a nuclear reactor. The multiplication factor M and its inverse value can be obtained from neutron counts measured by neutron detectors. In the core at a subcritical state with source strength S, when the total number of neutrons generated by fission reactions in all generations is F, that is, all generations are expanded to infinity, F can be expressed as [7]:

$$F = \frac{S}{1-k} . \quad \text{… (1)}$$

The multiplication factor M can be calculated by:

$$M = \frac{F}{S} = \frac{1}{1-k} \approx \frac{C_0}{C_i} . \quad \text{… (2)}$$

where C_0 and C_i are counting rates from detectors in the initial core and the ith core. If Eq. (2) is defined as the inverse of the multiplication factor, denoted as '1/M', it can be noted that the 1/M approaches zero as k_{eff} approaches 1. If the fuel mass is plotted on the x axis, while the 1/M is plotted on the y axis, the critical mass can be determined by finding the x-point where the '1/M' is zero by extrapolating from the measured data.

Table II presents the mass of ^{235}U in the nine fuel disks and four control rods in the improved AGN-201K benchmark model. In the approach to criticality experiment for AGN-201K, the CR control rod is incrementally inserted toward a critical state, whereas the SR#1, SR#2, and FR rods are fully inserted.

Therefore, the mass of ^{235}U fuel in the initial core (Fuel disk1 ~ Fuel disk9) with all control rod withdrawn is about 675.5 grams.

Table II: Mass of nine fuel disks and four control rods in the improved AGN-201K benchmark model (M11)

Case	^{235}U Mass (g)
Fuel disk 1	28.8
Fuel disk 2	33.8
Fuel disk 3	58.2
Fuel disk 4	58.2
Fuel disk 5	58.2
Fuel disk 6	94.6
Fuel disk 7	104.1
Fuel disk 8	104.5
Fuel disk 9	104.0
SR#1	14.4
SR#2	14.4
CR	14.4
FR	2.5
Total	690.1

* Fuel disk 7 includes a thermal fuse

Figure 3 plots the ratio of the counting rates, C_0/C_i from experiments and McCARD calculations using data from two channel detectors (i.e., Ch#1 and Ch#5).

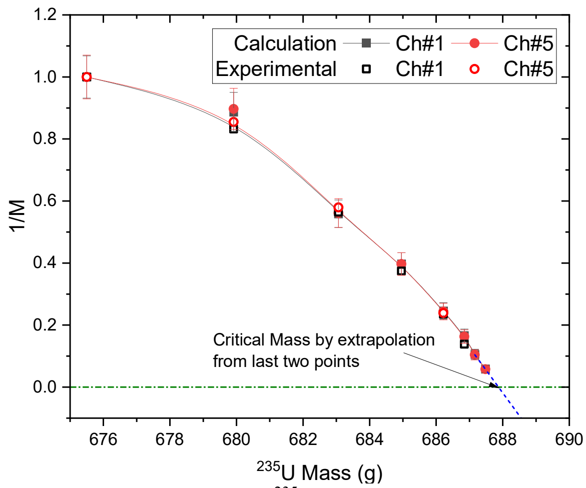

Fig. 3. Prediction of Critical ^{235}U mass (g) by the inverse of the multiplication factor 1/M

Table III: ^{235}U critical mass of AGN-201K reactor by the approach to critical experiment

Case	Channel	^{235}U Critical Mass (g)
FSAR		687
Experimental result	Ch#1	687.7
	Ch#5	688.4
McCARD result	Ch#1	687.8
	Ch#5	687.8

Table III shows the ^{235}U critical mass of AGN-201K extrapolated from the last two points. The predicted critical mass ranges from 687.7 g to 688.4 g, demonstrating excellent agreement with the reference (i.e., 687 gram) from the final safety analysis report [1].

3.2 FR Control Rod Worth

In a reactor experiment, a control rod worth can be estimated by various methods such as the positive period method, compensation method, and rod drop method. In the AGN-201K experiments, the FR control rod worth is calculated by solving the inhour equation with the reactor periods, τ , as shown in Eq. (3):

$$\rho = \frac{l_p}{\tau + l_p} + \frac{\tau}{\tau + l_p}\sum_{k=1}^{N}\frac{\beta_k}{1+\lambda_k \tau}, \qquad \dots (3)$$

where l_p is the prompt neutron lifetime, and β_k and λ_k indicate the effective delayed neutron fraction and decay constant for the *k*-th delayed neutron precursor group. The reactor period τ can be measured by the doubling time, t_{double}, which is the amount of time it takes for the power of a nuclear reactor to double. Table IV shows the initial CR and FR rod positions and reactor temperatures from 3 experimental data for the estimation of the reactor period. Two experimental data points were taken from the previous study and one new data point, highlighted in yellow, was added for FR rod worth problem.

Table IV: Initial control rod positions for the estimation of FR worth by positive period method

ID		Initial Control Rod Position*		
Problem	Exp.	CR (cm)	FR (cm)	Temp.
FRW001	T100-3	22.48	0	17.5
FRW002	T97-3	22.99	0	17.8
FRW003	T117-3	23.00	0	18.0

* FR position is the distance from the bottom of the reactor core tank.

Table V: Comparison between experimental and McCARD results for FR worth of AGN-201K

Problem ID	FR worth (pcm)			
	McCARD	Experimental Results		
		Ch #2	Ch #3	Ch #4
FRW001	213±11	206	209	208
FRW002	226±9	205	204	203
FRW003	217±8	-	212	213

Table V compares the experimental FR worth with the McCARD results. The FR worth from the reactor period measurements ranged from 203 pcm to 213 pcm. The McCARD results for three FR worth problems are 223±11 pcm, 226±9 pcm, and 217±8 pcm, respectively. It is worth mentioning that the experimental and calculated FR worth are in good agreement considering the uncertainties from measurements and stochastic calculations. Figure 4 presents the integral worth curve of the FR control rod in the FRW001 problem. It is observed that the McCARD results agree very well with the experimental data within one standard deviation.

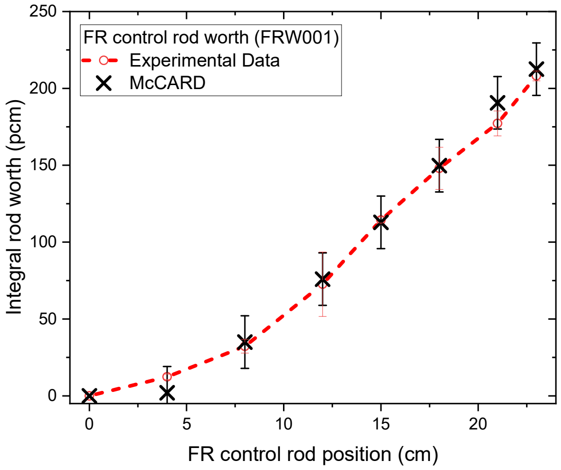

Fig. 4. Integral worth curve of FR control rod in FRW001 problem

In the AGN-201K reactor experiment educational program, measurements of count rates were conducted to analyze a transient behavior occurring after the FR control rod are fully inserted. Recently, advanced methods for a time-dependent MC (i.e., TDMC) neutron transport analysis have been successfully developed and implemented in McCARD [8]. Accordingly, to conduct transient analyses for the FR control rod insertion, the McCARD calculations are conducted with 50,000 neutrons and precursors. The time bin interval is set to 0.5 *ms*, and 100 convergence time bins and 500 precursor generation time bins are set for the initial state model. Figure 5 compares the experimental data from channel #2 and #4 with the McCARD transient fission rates. It is noted that the McCARD results show good agreements with the measurements.

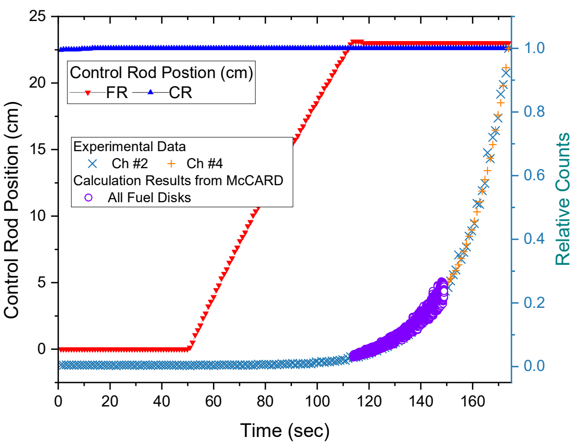

Fig. 5. Positions of FR and CR control rods and comparison measurements with McCARD transient analysis results

Table VI: Reactor periods estimation by measurement and McCARD transient analyses for FR rod full insertion

Problem ID	Reactor period (sec)			
	McCARD	Experimental Results		
		Ch #2	Ch #3	Ch #4
FRW001	16.3	17.3	16.3	15.9
FRW002	-	17.2	15.5	17.6

In the experiment, the reactor period can be calculated by its definition and t_{double}, as shown in Eq. (4). Meanwhile, the reactor period can be calculated from the exponential fitting of the McCARD time-dependent fission rates using Eq. (5).

$$\tau = \frac{t_{double}}{\ln 2}. \qquad \dots (4)$$

$$P(t) = P(0)e^{\frac{t}{\tau}}. \qquad \dots (5)$$

Table VI shows the reactor periods calculated by the measurements and the McCARD time-dependent fission rates. Figure 6 presents the exponential fitting for reactor period estimation in FRW001 FR control rod withdraw problem. It is confirmed that the reactor period from experiment results is very similar to the McCARD result.

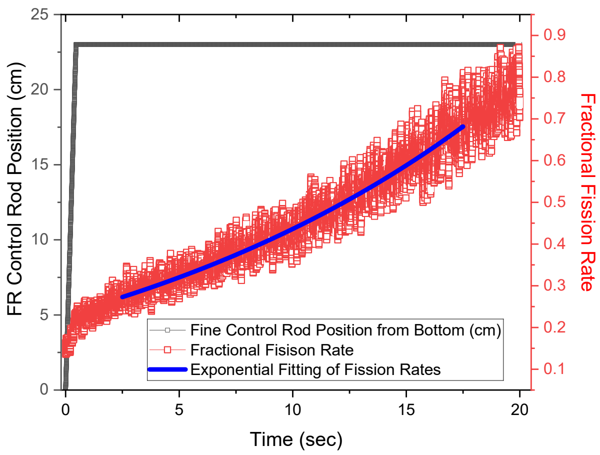

Fig. 6. Exponential fitting for reactor period estimation in FRW001 problem

3. Conclusions

In this study, an improved AGN-201K educational and research reactor benchmark model (*M11*) was developed. This improved benchmark model was verified for criticality problems at various critical rod positions, approach to criticality experiment problem, and FR rod worth measurement problem. The improved benchmark model was evaluated by comparing the experimental values with the calculated results by the

McCARD MC code. It's worth noting that the new benchmark model provides more accurate McCARD results compared to the previous benchmark model (*M10*).

Moreover, the most noteworthy point is that the recently developed McCARD transient modules are successfully demonstrated in the AGN-201K transient benchmark problems. From the results, the suitability of MC time-dependent analysis for practical and realistic applications has been confirmed.

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