McCARD Analysis for AGN-201K Reactor Physics Experiments

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1. Introduction

The AGN-201K reactor [1,2] at Kyung Hee University has been operated for research and education since 1982. AGN-201K consists of polyethylene disks embedding 19.5 wt. % enriched UO_2 particles, control rods, graphite reflector, lead and water shields. A small and complex reactor can be analyzed precisely by a Monte Carlo code because of its capabilities of using the continuous-energy cross section libraries and modeling the detailed geometry. AGN-201K has been analyzed using MCNP for its subcriticality experiment analysis [1].

In this paper, a detailed McCARD [3] model of AGN-201K is developed for its reactor physics experiment analyses. The control rod worth and the isothermal temperature coefficient (ITC) of AGN-201K are calculated by McCARD and compared with experimental results.

2. McCARD Model

Figure 1 shows the core configuration [4] for this analysis which consists of fuel disks, an aluminum baffle plate, and the control rods. The nine disks are designed with 644 grams of ^{235}U [2] in the form of uranium dioxide with enrichment of 19.5 ± 0.5 wt. % ^{235}U.

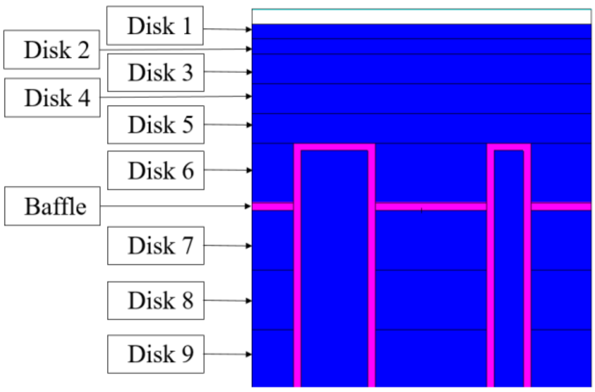

Fig. 1. Vertical View of Core

Table I provides the thickness of the fuel disks and the amounts of ^{235}U. Their diameter is 25.6 cm. Note that the 6th and 7th fuel disks are modeled to contain 104 g of ^{235}U while the 8th and 9th fuel disks contain 102 g considering the thermal fuse of 4 g ^{235}U [2]. The baffle plate with thickness of 0.5 cm is modeled to separate the core into the upper and lower parts. The top of fuel disk 1 is modeled by low density air as high as 1 cm. The composition of fuel is shown in Table II.

Table I: Fuel Disk Specifications

Fuel disk	Thickness (cm)	^{235}U mass (gram)	Gram density (g/cm^3)
1	1.0	29.0	1.22561
2	1.0	29.0	1.22561
3	2.0	58.0	1.22561
4	2.0	58.0	1.22561
5	2.0	58.0	1.22561
6	4.0	104.0	1.32057
baffle	0.5	0.0	2.70200
7	4.0	104.0	1.32057
8	4.0	102.0	1.27118
9	4.0	102.0	1.27118
Total	24.5	644.0	-

Table II: Composition of Fuel

Nuclides	Normalized gram density (gram/cm^3)
^{1}H	0.10524
C	0.62725
^{16}O	0.03176
^{235}U	0.04597
^{238}U	0.18978

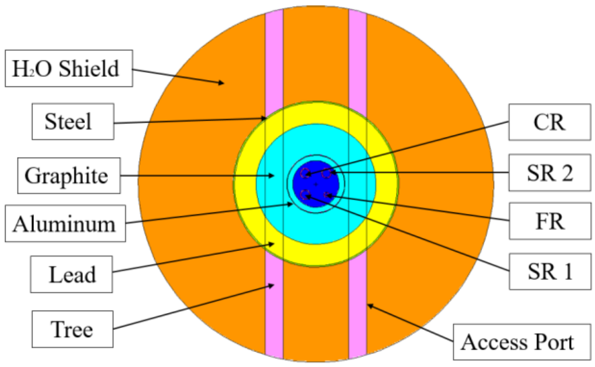

Fig. 2. Planar Configuration of AGN-201K

Figure 2 shows the planar configuration of AGN-201K. The AGN-201K reactor has four control rods – two safety rods (SR 1 and SR 2), one coarse rod (CR), and one fine rod (FR) – which can be inserted by 16 cm from the bottom of the fuel disk 9 in a total flight length of 24 cm [4] within vertical control element tubes. A reactor operator can insert negative reactivity by withdrawing the control rods. The composition of control rods is the same as the fuel disks. The thicknesses of its cladding and control element tube made of aluminum are 0.25 cm and 0.25 cm, respectively [4]. The FR contains 2.5 g of ^{235}U [2] with the inner diameter of 2 cm [4]. Then AGN-201K becomes to have the total ^{235}U amount of 690 g [2] in the fuel disks and the control rods. The geometrical data of the control rods for AGN-201M [4] at UNM are used in this analysis.

Table III: Control Rod Specification

Parameter	SR 1	SR 2	CR	FR
Fuel radius (cm)	2.25	2.25	2.25	1.00
Outside radius (cm)	2.50	2.50	2.50	1.25
Control element tube thickness (cm)	0.25	0.25	0.25	0.25
^{235}U Mass (gram)	14.50	14.50	14.50	2.50

Figure 3 shows the vertical configuration of AGN-201K. The core is surrounded by graphite reflector. A thin aluminum barrier divides the graphite reflector into two regions. Lead shield with thickness of about 10 cm surrounds the graphite reflector. This reactor core is immersed in a water tank with radius of 98 cm and height of 157.36 cm. AGN-201K has four access ports and a glory hole. Access ports filled with graphite, lead, and wood. The glory hole is modeled to be empty.

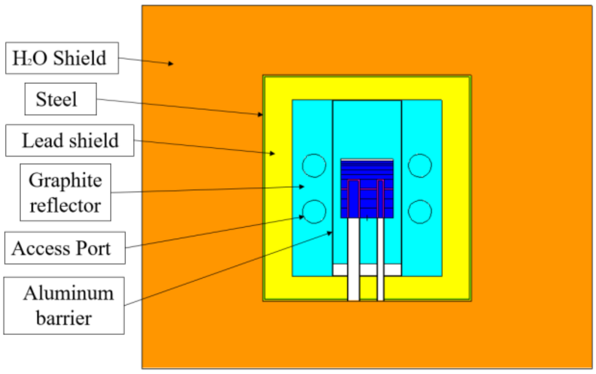

Fig. 3. Vertical View of AGN-201K

3. McCARD Analysis for the FR Worth

3.1 FR worth measurement

When an excess positive reactivity, ρ^{ex}, is inserted into a reactor from the critical state, it can be estimated by measuring the reactor period, T, in the positive period method [6]. Using the measured value of T, ρ^{ex} can be calculated by the inhour equation:

$$\rho^{ex} = \frac{l_p}{T+l_p} + \frac{T}{T+l_p}\sum_{i=1}^{6}\frac{\beta_i}{1+\lambda_i T}, \quad (1)$$

where l_p is the prompt neutron lifetime and β_i and λ_i are the effective delayed neutron fraction and the decay constant, respectively, for delayed neutron precursor group i. Table IV shows β_i and λ_i calculated by McCARD using ENDF/B-VII.1.

Table IV: Kinetics Parameters of AGN-201K

i-group	β_i	λ_i (1/sec)
1	0.000264	0.013337
2	0.001379	0.032735
3	0.001319	0.120787
4	0.002907	0.302837
5	0.001196	0.894964
6	0.000503	2.853540
sum	0.007568	-

Three BF_3 ionization chambers (channel 2, 3, and 4) were used to measure the reactor period in the experiment. The FR was sequentially inserted by 4, 7, 10, 13, 16, 19, and 23 cm. When the FR is fully inserted, the total insertion length becomes 23 cm. When the flux level of the detector became 150% from an arbitrary level, the duration time was measured by stopwatch. Then the reactor period can be calculated as

$$T = \frac{t}{\ln(1.5)}, \quad (2)$$

where t is the 150% elapsed time. After measuring the excess reactivity corresponding to an inserted FR position, the CR was withdrawn to make the core re-critical. Table V shows the reactor period measurements at each FR position for the three detectors and Table VI the final reactivity worth of the FR.

Table V: Compensation Method Experiment Data

Step	Rod position (cm)		Reactor Period (sec)		
	CR	FR	CH2	CH3	CH4
Critical	21.87	0.00			
1	21.87	4.00	811.82	761.27	874.31
Re-critical	21.67	4.00			
2	21.67	7.00	567.25	554.51	630.14
Re-critical	21.47	7.00			
3	21.47	10.00	275.40	274.58	295.96
Re-critical	21.05	10.00			
4	21.05	13.00	227.31	214.98	238.62
Re-critical	20.58	13.00			
5	20.58	16.00	191.76	186.82	193.61
Re-critical	20.05	16.00			
6	20.05	19.00	173.26	168.94	189.29
Re-critical	19.48	19.00			
7	19.48	23.00	116.53	118.38	124.55

Table VI: The Experiment Results about Fine Rod Worth

	CH2	CH3	CH5	Avg.	SD
FR worth (pcm)	219.36	223.03	207.93	216.77	6.43

3.2 McCARD FR Worth Calculation

The McCARD eigenvalue calculations to calculate the FR worth are performed with 3,000,000 histories per cycle on 50 inactive and 400 active cycles using the continuous-energy cross section libraries produced from ENDF/B-VII.1 and thermal scattering libraries, $S(\alpha,\beta)$, of water, graphite, and polyethylene. For the verification purpose, MCNP5 calculations are also done with 3,000,000 histories per cycle on the same numbers of cycles.

Table VII shows comparisons of the effective multiplication factors (k_{eff}'s) calculated by McCARD and MCNP5 for the all-rod-in (ARI) and the FR withdrawal (FRO) states. From the table, we can see that k_{eff}'s calculated by McCARD agree well with those from MCNP5 within their 95% confidence intervals.

Table VII: Comparisons of k_{eff}'s Calculated by McCARD and MCNP5

Control rods status	k_{eff}	
	McCARD (SD)	MCNP5 (SD)
ARI	1.02901 (0.00002)	1.02905 (0.00002)
FRO	1.02699 (0.00002)	1.02708 (0.00002)

Table VIII shows the comparisons of the FR worth calculated from the results of Table VII with the experimental results. From the table, one can see that the McCARD estimate of 191.15 pcm is different by 11.8% with the experiments while it agrees well with MCNP5's considering its statistical uncertainty.

Table VIII: Comparisons of the FR worth Calculated by McCARD and MCNP5 with Experiments

Fine rod worth (SD) (pcm)		
Experiment	McCARD	MCNP5
216.77 (6.43)	191.15 (2.68)	187.34 (2.68)

To investigate the effect of the fuel enrichment uncertainty, McCARD calculations are performed by varying the fuel enrichment of the FR as 20.5 wt. %, 21 wt. %, and 21.5 wt. %. Table IX shows comparisons of the FR worth for the FR fuel enrichment. From the table, one can see that the difference of the McCARD results becomes 8.8% with the enrichment of 21.5%. The sensitivity of the FR worth for the fuel enrichment is 3.3 pcm/wt. %.

Table IX: FR worth for FR enrichment

Enrichment (wt. %)	^{235}U mass (gram)	FR Worth (SD) (pcm)
19.50	2.50	191.150 (2.68)
20.50	2.63	191.124 (2.68)
21.00	2.69	194.905 (2.68)
21.50	2.75	197.753 (2.68)

4. McCARD Analysis for the ITC Experiment

4.1 ITC Experiment

The critical FR positions were searched with varying the ambient temperature from 19 ºC to 16.5 ºC at the same conditions to measure the ITC. Table X shows the FR positions at the critical state with changing the temperature by 2.5 ºC. Then, using the differential rod worth of the FR, the ITC corresponding to the FR critical positions was calculated as -21.3 pcm/ºC.

Table X: Critical FR Positions According to Temperature Change

Step	Critical control rod position (cm)				Analog console temp.(ºC)
	SR 1	SR 2	CR	FR	
1	23.00	23.00	21.07	14.41	19.0
2	Temperature Change				16.5
3	23.00	23.00	21.07	8.68	16.5

4.2 McCARD Calculation of ITC

McCARD eigenvalue calculations are performed with 1,000,000 histories per cycle on 50 inactive and 400 active cycles using the continuous-energy cross section libraries produced from ENDF/B-VII.1.

When the ambient temperature is changed from 19 ºC to 16.5 ºC, the inserted reactivity is calculated by McCARD. The thermal scattering libraries at 296K are used. The inserted reactivity is -12.31 ± 5.36 pcm. Divided by 2.5 ºC, the ITC is -4.92 ± 2.14 pcm/ºC, which is 4.3 times smaller than the experiment result. To investigate the effect of the thermal scattering libraries of water, graphite (GP), and polyethylene (PE), McCARD calculations are performed by varying their temperature. Table XI shows the inserted reactivity for the changed temperature of thermal scattering libraries.

Table XI: The Inserted Reactivity According to $S(\alpha,\beta)$ Temperature Change

Mat.	Temp. (K)		Reactivity change (SD) (pcm)	TC (SD) (pcm/ºC)
	State 1	State 2		
PE	350.0	296.0	-745.9 (5.3)	-14.18 (0.10)
GP	400.0	296.0	+148.3 (5.2)	+1.43 (0.05)
H_2O	350.0	293.6	+8.1 (5.1)	+0.15 (0.10)

The results show that the effect of the PE is dominant as -14.18 pcm/ºC. When these thermal scattering cross sections are considered, the ITC is -17.53 ± 2.14 pcm/ºC. McCARD calculation is different by 17.7% with the ITC experiment.

5. Conclusion

The AGN-201K experiments on the FR worth and the ITC are analyzed by McCARD. The difference of the FR worth calculated by McCARD is 11.8% comparing to the experimental result. The sensitivity of the FR worth for the fuel enrichment of FR is analyzed by McCARD. The sensitivity of the FR worth for the fuel enrichment is 3.3 pcm/wt. %.

When the thermal scattering libraries with the changed temperature are considered, the ITC calculated by McCARD is -17.53 ± 2.14. The McCARD calculation of the ITC shows 17.7% difference comparing to the experimental result.

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