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Preliminary Benchmark Evaluation of AGN-201K Educational and Research Reactor

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1. Introduction

The AGN-201K educational and research reactor has been in operation since it had installed at the global campus of Kyung Hee University (KHU) at 1982. The AGN-201K is the only educational-proposed reactor in South Korea and had been utilized in various reactor experiment educational program.

The core of AGN-201K reactor is comprised of the 9 fuel discs that are made of the homogeneous mixture of polyethylene and uranium dioxide. The reactor is controlled by two safety rods (SR#1, SR#2), one coarse rod (CR), and one fine rod (FR). The control rods are made of the same material as the fuel discs in the core. The core is surrounded by a 20-cm thick layer of graphite, along with a 10-cm thick lead block for a neutron moderator and radiation shield. Originally, the AGN-201 reactor, former model of the AGN-201K was designed as a low power (0.1 watt) nuclear reactor, but KHU reinforced the facility to increase the licensed maximum power to 10 watt. Accordingly, the AGN-201K has a 60 cm concrete shielding wall.

Up until now, a wide range of efforts have been dedicated to comparing the computational calculations and experimental results for AGN-201K. Unfortunately, sufficient information was unavailable for the generation of a highly detailed AGN-201K benchmark model. In this study, we propose new preliminary benchmark problem of AGN-201K by integrating the AGN-201K data from publicly available reports, article and actual measurements. [1-6]

2. AGN-201K Benchmark Model Development

2.1 Configuration of AGN-201K Benchmark

Similar to the other AGN-201 reactors, the AGN-201K core consists of two 1cm thick, three 2cm thick, four 4cm thick fuel disks. But a comprehensive data of the fuel composition and dimensions may be found. For the defining and analyzing the AGN-201K benchmark, the reliable references were employed in the confirmation of the fuel data. First of all, we can access the old data from the references. At 1961, W. B. H. Cooke published a research report on the behavior of the AGN-201 reactor at high power levels [1]. The report of the results provided some general characteristics of the AGN-201 reactor. The final safety analysis report (FSAR) [2] of the AGN-201K provides the measurement values of the fuel disks such as the diameter, thickness, and mass. Recently, Oak Ridge National Laboratory (ORNL) proposed a new subcritical assembly, which use the fuel disks of the AGN-201M reactor [3]. The report for the new subcritical assembly provided the dimensions and mass specification for the fuel disks and the control rods.

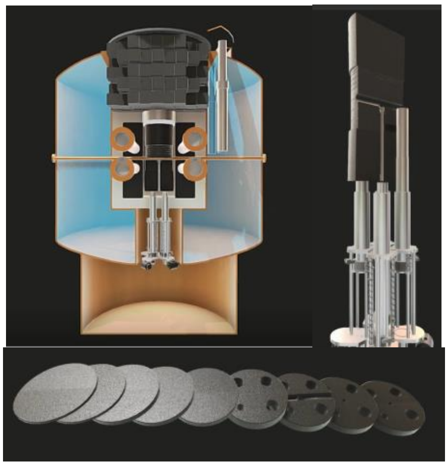

Fig. 1. Cross section of the AGN-201K reactor, fuel disks, and control rod system

In summary, the ^{235}U enrichment of the fuel disks are ranged from 19.5 ~ 19.95 wt. % while the diameter is about 25.6 cm. In the lower fuel disks, the hole diameter of the safety control rods and the coarse rod is about 2.55 cm and the diameter of FR is about 1.47 cm.

Table I shows the thickness and mass of the nine fuel disks in the AGN-201K core from FSAR [2] whereas Table II provides the control rod specifications of the AGN-201M from the ORNL report [3]. The fuel mass densities were calculated by the masses and volumes.

Table I: Specifications of Fuel Disks from AGN-201K FSAR

Disk No.	Fuel No.	Thickness (cm)	Mass (g)	Density (g/cm^3)
1	20491	1	630	1.223
2	20494	1.1	740	1.261
3	20480	2	1275	1.238
4	20479	2	1275	1.238
5	20472	2	1275	1.223
6	20460	4	2070	1.233
7	20468	4	2045	1.205
8	20458	4	2135	1.208
9	20457	4	2125	1.198

Table II: Specifications of Control Rods from AGN-201M

CR	Diameter (cm)	Mass (g)	Density (g/cm^3)
SR#1	5.5	315	1.241
SR#2	5.5	315	1.240
CR	5.5	315	1.240
FR	2	58	1.173

The availability of precise data on the isotope composition in the fuel disks is limited because the fuel disks in the core are sealed. We selected the mass fraction data from the reference as shown in Table III.

Table III: Isotopic-wise Mass Fraction of Fuel

Isotope	Mass Fraction (%)
^{235}U	4.5
^{238}U	18.1
^{16}O	3.0
C-Nat.	63.7
^{1}H	10.6

2.2 McCARD AGN-201K Benchmark Model

Figure 2 shows the planer and vertical views of AGN-201K benchmark McCARD model [4], which are visualized by the McView utility [7].

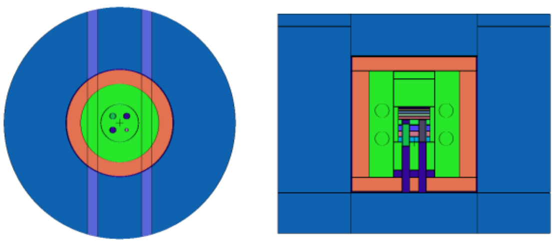

Fig. 2. Y-Z and X-Y plane cross section of the AGN-201K benchmark model by McView

To examine the AGN-201K benchmark model, the criticality was calculated by the McCARD Monte Carlo neutron/photon transport code [8] at various critical states due to control rod positions. In this study, all McCARD calculations are performed using ENDF/B-VII.1 neutron reaction cross section and thermal scattering cross section. In the AGN-201K benchmark, the Doppler-broadened cross sections for the MC calculations for various specific temperatures are essential. In order to resolve this problem effectively, the on-the-fly Doppler-broadening method implemented in the McCARD was used in the AGN-201K benchmark problem [9].

3. Preliminary Evaluation of AGN-201K Benchmark

3.1 Criticality

Table IV shows the CR and FR rod positions and reactor temperatures from a total of 18 experimental data.

Table IV: Control Rod Positions at the Critical State

ID		Control Rod Position (cm)*		
Problem	Exp.	CR (cm)	FR (cm)	Temp.
CRI001	T86-1	19.96	20	19.8
CRI002	T94-1	20.81	15	19.2
CRI003	T94-2	19.83	20	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	19.9
CRI007	T111-2	21.37	19	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	17.5
CRI014	T101-1	20.32	22.38	19.7
CRI015	T103-1	21.3	18.38	19.8
CRI016	T104-1	20.33	22.64	19.4
CRI017	T105-1	20.8	20.62	19.8
CRI018	T105-2	22.1	15	19.8

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

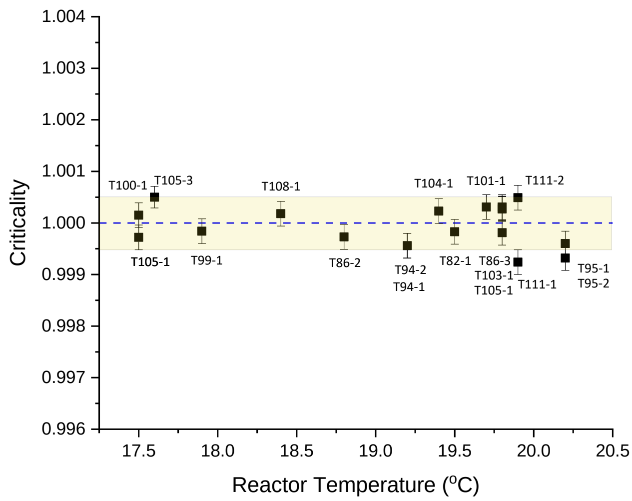

Fig. 3. Comparison of k_{eff} calculated by McCARD AGN-201K benchmark model and experimental values

The average k_{eff} from the 18 criticality problems is about 0.99994 and its standard deviation is about 40 pcm. The uncertainties of multiplication factors come from the uncertainty of the CR and FR positions and the reactor temperature. Because the thermal probe for analog core temperature measurement is located inside the water tank, the uncertainty of the measured temperature can occur due to the difference of temperatures between the core and the water tank.

3.2 FR Control Rod Worth

In the AGN-201K reactor physics experiments, FR worth can be calculated by the inhour kinetic equation with the reactor periods measured from positive period method and compensate method. Eq. (1) shows the inhour kinetic equation.

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

where l_p is the prompt neutron lifetime. β_k and λ_k are the effective delayed neutron fraction and decay constant for k-th delayed neutron precursor group whereas τ is the reactor period, which can be measured by the positive period method and the compensate method. In general, the reactor period can be estimated by the counts from the neutron detectors. In AGN-201K, there are seven neutron detectors (Ch #1~Ch #7). We selected three BF3 ionization chambers (i.e, Ch #2, Ch#3, and Ch #4) to measure the neutron counts.

Table V: 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	23.00	0	19.9

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

Table V shows the initial CR and FR rod positions and reactor temperatures from 2 experimental data for the reactor period estimation. At each initial state, the FR fully inserted and the counts at each channel are recorded as time elapsed as shown in Figure 4. The reactor periods can be estimated by the exponential fitting for each channel count data.

Table VI: Kinetic Data for the FR Worth Estimation

Precursor Group	Original Data		Kinetic Data from McCARD	
	λ_k	β_k	λ_k	β_k
1	0.0124	0.00033	0.0134	0.00026
2	0.0305	0.00220	0.0327	0.00138
3	0.1110	0.00196	0.1208	0.00132
4	0.3010	0.00397	0.3028	0.00291
5	1.1300	0.00115	0.8950	0.00120
6	3.0000	0.00047	2.8535	0.00050
Total	-	0.01009	-	0.00757
l_p (sec)	$1.0\text{x}10^{-4}$		$2.0\text{x}10^{-4}$	

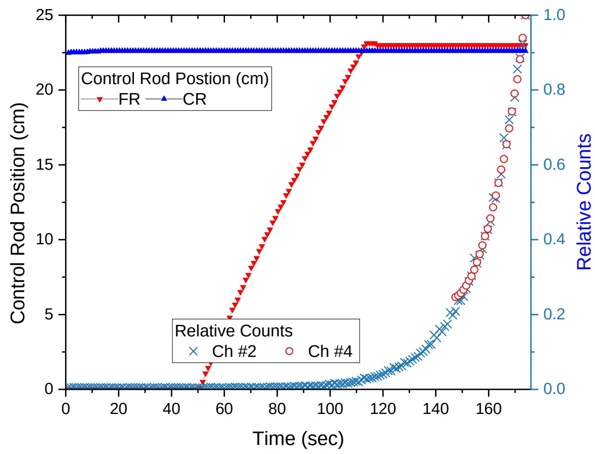

Fig. 4. Positions of fine and coarse control rods and counts of Ch#2 and Ch#4 for positive period method (FRW001)

Table VI presents the kinetic parameters used to calculate the FR worth by Eq. (1). The original data were taken from the reference and old data. Recently, Seoul National University observed that the variations in the kinetic data result in significant discrepancies in the control rod worth analysis [4]. In this study, the precise kinetic parameters were token from the McCARD calculations for AGN-201K benchmark model.

Table VII: 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	221±11	210	219	211
FRW002	227±11	212	210	199

Table VII compared the experimental FR worth with the McCARD results. The FR worth from the reactor period measurements ranged from 199 pcm to 219 pcm. The McCARD results for FRW001 and FRW002 problems are 221±11 pcm and 227±11 pcm, respectively. It is noted that the experimental and calculated FR worth are in good agreement within two standard deviations.

3.3 Thermal Flux Distribution

In the AGN-201K, the thermal flux can be measured by the neutron activation analysis (NAA) of gold-wire samples, which are located at the glory hole as shown in Figure 5. Table VIII shows the initial CR and FR rod positions and reactor temperatures from 6 experimental data. In the McCARD calculations, the cut-off energy for thermal energy region was set as 0.625 eV. For the normalization of the experimental and calculated flux distributions, the maximum value gets transformed into 1. Figure 6 compared the normalized thermal flux distribution from NAA experimental results with that by the McCARD calculations for AGN-201K benchmark model. The average RMS difference of the thermal flux distribution is about 4.0%.

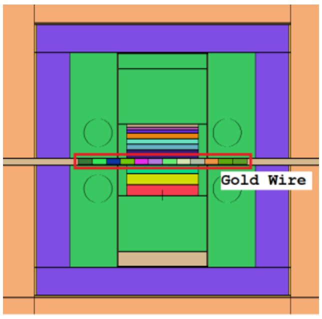

Fig. 5. Location of gold-wire samples for thermal neutron flux measurement in the glory hole

Table VIII: CR and FR positions and temperature for the thermal flux measurement

ID		Initial Control Rod Position*		
Problem	Exp.	CR (cm)	FR (cm)	Temp.
FLX001	T95-4	20.65	13.92	20.2
FLX002	T97-4	23.00	0	19.9
FLX003	T99-4	19.9	22.87	17.9
FLX004	T100-4	21.05	15	17.5
FLX005	T101-4	20.32	22.38	19.7
FLX006	T108-4	20.44	22.59	18.4

* CR and FR positions are the distance from the bottom of the reactor core tank.

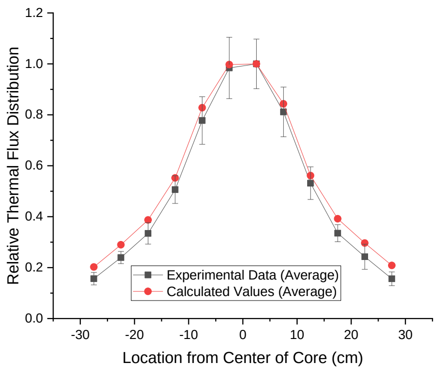

Fig. 6. Normalized thermal flux distribution in the AGN-201K benchmark model

3.4 Isothermal Temperature Coefficients

The AGN-201K benchmark provides the experimental results for isothermal temperature coefficients (ITC). The ITC can be measured using the reactivity changes estimated from the changes in FR positions due to the change of the temperature. Table IX shows the CR and FR positions due to the change of the temperatures for ITC calculations. Table X shows the experimental and calculated ITC results for the three problem cases (i.e., ITC001 ~ ITC003). For the ITC, the McCARD calculations were performed with the two temperature points (i.e., 300.15 K and 303.15 K) because we have only two polyethylene thermal scattering cross sections. In the near future, the thermal scattering cross section files at various temperature points will be prepared and the precise analyses for ITC benchmark problems will be performed. The difference between the experimental and calculated ITCs ranged from 7% to 43%.

Table IX: CR and FR positions due to the changes of temperatures for ITC calculations

ID	Initial Condition			After Temp. Change	
Prob.	CR (cm)	FR (cm)	Temp.	FR (cm)	Temp.
ITC001	20.55	21.37	19.9	19.00	18.3
ITC002	21.50	17.57	20.2	13.69	18.4
ITC003	21.36	19.17	19.9	15.32	17.5

* CR and FR positions are the distance from the bottom of the reactor core tank.

Table X: Isothermal Temperature Coefficients experimental and McCARD results

Problem ID	ITC (pcm/°C)	
	McCARD*	Experimental Results
ITC001	-15.74±3.8	-16.8
ITC002		-27.5
ITC003		-21.6

* For ITC analysis, The McCARD calculation were performed at 300.15 K and 303.15 K temperature points.

4. Conclusions

In this study, a preliminary AGN-201K research reactor benchmark was introduced to provide researchers with the tool to verify and validate the high-fidelity reactor simulation codes and methods. The preliminary AGN-201K benchmark provides the control rod positions at the critical states, FR worth, thermal flux distribution at the glory hole, and ITC.

The preliminary AGN-201K benchmark was evaluated by comparing the experimental values with calculated results by the McCARD simulation code. The experimental and calculated results were in good agreements. In the near future, more updates and evaluations of the AGN-201K benchmark are forthcoming.

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REFERENCES

[1] William B. H. Cooke, "Predicted Behaviour of the AGN 201 Reactor at High Power Levels," United States Naval Postgraduate School, California, 1961.
[2] "Final Safety Analysis Report for AGN-201K," Kyung Hee University, 2021.
[3] D. Bowen, A. Holcomb, S. Hart "Feasibility Study for a Subcritical Assembly at the Oak Ridge National Laboratory," ORNL/TM-2020-1598, Oak Ridge National Laboratory, 2020.
[4] K. Song, H. J. Shim, M. H. Kim "McCARD Analysis for AGN-201K Reactor Physics Experiments," Transactions of the Korean Nuclear Society Autumn Meeting, Yeosu, Korea, October 25-26, 2018.
[5] J. H. Kim and M. H. Kim "Validation of AGN-201K Design Data with Combination of Numerical Analysis and Experiments," Transactions of the Korean Nuclear Society Virtual spring Meeting, May 13-14, 2021.
[6] K. C. Ruzich and W. J. Sturm "Hazard Summary Report for the Argonne AGN-201K reactor," ANL-6510, Argonne National Laboratory, 1962.
[7] S. J. Jeong and H. J. Shim "McView: McCARD Input Visualization Tool," Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October 20-21, 2022.
[8] H. J. Shim et al., McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis, Nuclear Engineering and Technology, Vol.44, p 161-176, 2012.
[9] S. M. Kang et al., Development of an On-The-Fly Doppler Broadening Module in McCARD, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 29-30, 2014.