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A Computational Simulation of Sub-Criticality Measurement using MCNP6 in zero-power reactor AGN-201K

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1. Introduction

It is very important to maintain sub-criticality of nuclear facilities such as spent fuel storage facilities and nuclear reactor for preventing an excursive chain reaction which may lead to a criticality accident. In particular, the accurate measurement of sub-criticality using detector signals from the reactor core is very helpful to safely operate experimental or research reactors. As the results, the several measurement methods of sub-criticality to verify that the nuclear facilities are maintained under subcritical has been developed. The one of the popular noise analysis methods for measuring sub-criticality is the Rossi-alpha method which measures the time distribution of a neutron detector placed in a reactor system, takes a count as the time origin, and obtains the prompt period.

In this work, a computational simulation of sub-criticality measurement using MCNP6 for several sub-critical conditions in AGN-201K which is a unique zero power research and training reactor in our country is performed to generate fission counts in a time series and these fission counts are used to estimate sub-criticality based on the Rossi-alpha method. Then, the results of the simulated sub-criticality are compared with the calculated sub-criticality using MCNP6 eigenvalue mode.

2. Description of AGN-201K Model

The AGN (Aerojet General Nucleonics)-201K reactor which was donated from Colorado State University in 1976 is a zero power reactor for research and education. Its licensed maximum power is 10 Watt [1]. The core of this reactor is comprised of 10 disk type fuels in which UO_2 is homogeneously mixed with polyethylene. The uranium enrichment of the fuel is slightly less than 20 wt% [1]. The active core height is 25 cm. The core is surrounded by 23.3 cm radial and 26.8 cm thick axial graphite reflectors. The graphite reflectors are followed by a 10 cm thick lead layer for gamma shielding. These components are surrounded by a 4.06 cm thick stainless steel layer, which is placed in a water tank [2]. The reactor is started up by inserting a 10 mCi Ra-Be neutron source into the core and the reactivity is controlled using the control rods of which its composition is the same as the fuel [1]. This reactor has four control rods : 2 Safety Rods (SR), 1 Coarse Rod (CR), and 1 Fine Rod (FR). During the reactor operation after start up, the power is actually controlled using CR and FR. The reactor has four beam ports and one glory hole for experiments using neutrons [1]. The axial and radial configurations modeled using MCNP6 are shown in Figs. 1 and 2, respectively.

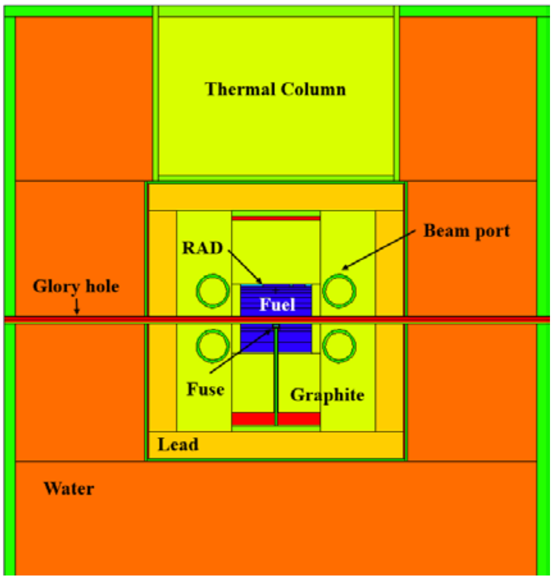

Fig. 1. Axial configuration of the AGN-201K

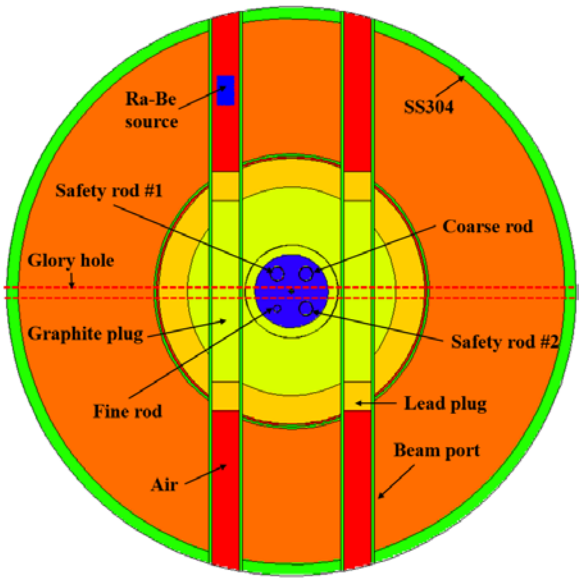

Fig. 2. Radial configuration of the AGN-201K

3. Review of Rossi-Alpha Method

In this sub-section, the Rossi-alpha method which is one of the famous noise analysis methods is simply reviewed. The Rossi-alpha method assumes random neutron sources over time and the probability representing auto-correlation of the detector signals in time can be represented by taking prompt fission chains into consideration only [3]. The probability of detecting two random events is given by

$$p_r(t_1,t_2)\Delta t_1\Delta t_2 = F^2\varepsilon^2\Delta t_1\Delta t_2. \quad (1)$$

where F is the average fission rate, ε is the detector efficiency, Δt_1 and Δt_2 are the small time interval around t_1 and t_2 in which the detection events occur. The probability of detecting a correlated neutron detection event near time t_1 (i.e., the probability that the neutrons generated from a fission reaction at t_0 are detected at $t_1+\Delta t_1$) is given by

$$p_1(t_1)\Delta t_1 = \varepsilon v\nu\Sigma_f e^{-\alpha(t_1-t_0)}\Delta t_1. \quad (2)$$

where ν is the average number of neutrons generated by one fission, v is the neutron velocity, and Σ_f is the macroscopic fission cross section. On the other hand, the probability that the remaining (ν−1) neutrons generated by the fission at t_0 are detected at time $t_2+\Delta t_2$ is given by

$$p_2(t_2)\Delta t_2 = \varepsilon v(\nu-1)\Sigma_f e^{-\alpha(t_2-t_0)}\Delta t_2. \quad (3)$$

So, the total probability of detecting two correlated neutron counts is given by

$$\begin{aligned} p_c(t_1,t_2)\Delta t_1\Delta t_2 &= \int_{-\infty}^{t_1} p(t_1)\Delta t_1 p(t_2)\Delta t_2 F dt_0 \\ &= F\varepsilon^2\frac{D_\nu(1-\beta)^2}{2(\beta-\rho)\Lambda}e^{-\alpha(t_2-t_1)}\Delta t_1\Delta t_2. \end{aligned} \quad (4)$$

where β is the delayed neutron fraction, ρ is the reactivity, Λ is the neutron generation time, and D_ν is the Diven's factor. The final total probability of detecting two neutron counts is obtained by summing the correlated and uncorrelated probabilities, which is given by

$$P(\tau)\Delta t_1\Delta t_2 = F\varepsilon^2\left(F+\frac{D_\nu(1-\beta)^2}{2(\beta-\rho)\Lambda}e^{-\alpha\tau}\right)\Delta t_1\Delta t_2. \quad (5)$$

where τ is the time interval between two detecting time points ($=t_2-t_1$). The auto-correlation of the measured detector signals can be processed using the following equation which is supposed to be equivalent to Eq.(5) :

$$P(\tau) = R(C_i,C_{i+k}) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{C_i-\mu_{C_i}}{\sigma_{C_i}}\right)\left(\frac{C_{i+k}-\mu_{C_{i+k}}}{\sigma_{C_{i+k}}}\right) \quad (6)$$

where R is the Pearson correlation coefficient, N is the total number of time bins, μ_{Ci+k} and σ_{Ci+k} are the mean value and standard deviation of the series of counts skipped by k time bins from the first time bin, respectively, and t is $k\Delta t$ (Δt is the time interval of a single time bin). The form of Eq.(5) means that the prompt decay constant can be obtained using the least square fitting for the data obtained with Eq.(6) as follows [4]:

$$\text{Fitting Curve} = A*\exp(-\alpha*\tau)+B. \quad (7)$$

After the determination of the prompt decay constant, the effective multiplication factor can be calculated using

$$k_{eff} = \frac{1}{1-\beta+\alpha\Lambda}. \quad (8)$$

4. Simulation Results

We considered four different subcritical conditions having different control rods' positions. Table I describes the positions of control rods for the four subcritical conditions. In Table I, one supercritical and one nearly critical conditions are also given. The supercritical condition corresponds to ARI (All Rods In). First, we estimated the effective multiplication factors, the effective delayed neutron fractions and neutron generation times for these conditions using MCNP6 (k-code mode) and cross section library based on ENDF/B-VII.r1. In these calculations, 50 inactive cycles, 300 active cycles, and 30000 histories per each cycle, which gave ~30 pcm standard deviation. As shown in Table I, the first subcritical condition (SCR1) corresponds to the condition in which SR#1, SR#2, and FR are fully inserted but CR is inserted up to 21cm. The sub-criticality level of this condition is about 1000 pcm Δk. The second criticality condition (SCR2) represents the rod positions in which SR#1 and SR#2 are inserted up to 18cm, CR is fully withdrawn, and FR is inserted up to only 1cm. This condition corresponds to ~2000 pcm Δk sub-criticality level. In the third subcritical condition (SCR3), SR rods are inserted up 12 cm and all the other rods are fully withdrawn, which corresponds to a quite large sub-criticality level of ~3030 pcm Δk. The last subcritical condition (SCR4) models the ARO (All Rods Out) state giving 4104 pcm Δk. Next, the simulation of the fission counts (fission count tally) as time is performed using the MCNP6 fixed source mode.

Table I. Multiplication factor and kinetic parameters according to the considered conditions

Condition	k_{eff}	STD (pcm)	β_{eff}	Λ (μsec)	Inserted rod position (cm)				Thermal Column
					SR#1	SR#2	CR	FR	
ARI	1.00171	29	0.00770	53.52871	23	23	23	23	Graphite
Nearly critical	1.00015	26	0.00744	54.07302	23	23	21	23	
SCR1	0.99069	30	0.00757	55.68657	23	23	7	23	
SCR2	0.98010	28	0.00777	58.26246	18	18	0	1	
SCR3	0.96970	27	0.00757	61.47256	12	12	0	0	
SCR4 (ARO)	0.95896	29	0.00757	63.83966	0	0	0	0	

In these simulations, a isotropic uniform cylindrical volume source emitting 3.6 MeV neutrons in beam port shown in Fig. 2 is simulated by considering uniform emission of 20,000,000 neutrons during the simulation duration of 0.5 sec. Also, we applied the weight window technique to increase the fission count tally. Fig. 3 shows the mesh divisions for the application of the weight window technique. In this simulation, the fission events are counted in each 10 μsec and they are tallied over the active fuel regions. With the weight window technique, the statistical errors of fission count tallies for each time bin were estimated to be ~5% which is acceptably small.

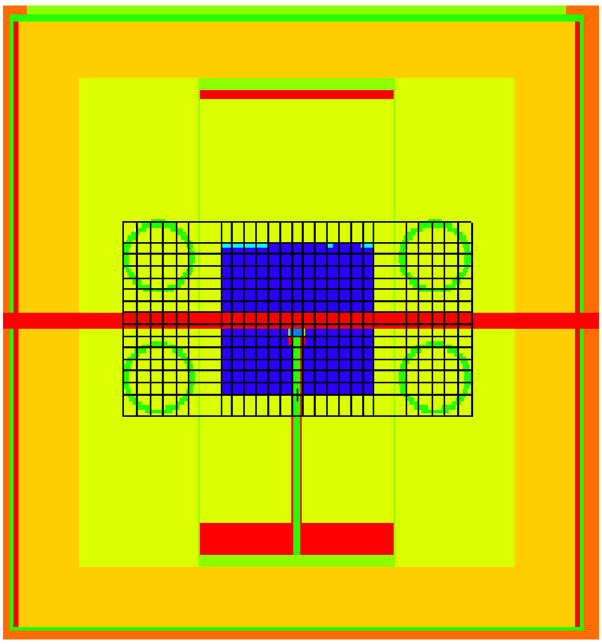

Fig. 3. Weight window mesh division on the reactor

The simulated fission count tallies within each time bin of 10 μsec are shown in Fig. 4. Fig. 4 shows that the simulated fission counts as time are well stabilized within short time for all the cases. Fig. 5 compares the auto-correlation coefficients and the fitted values using Eq.(7) versus gate time. As expected, the auto-correlation coefficient decreases as the gate time. The final estimated multiplication factors using Eq.(8) are compared with the reference effective multiplication factors obtained with MCNP6 k-code mode calculations in Table II. As shown in Table II, the estimated multiplication factors using the Rossi-alpha method and the simulated fission count signals have quite good agreements with the reference effective multiplication factors obtained with MCNP6 k-code mode calculations. In particular, it is noted that the discrepancy between the multiplication factors is quite small even for the extremely large subcritical level case. The maximum discrepancy is ~34 pcm *Δk*.

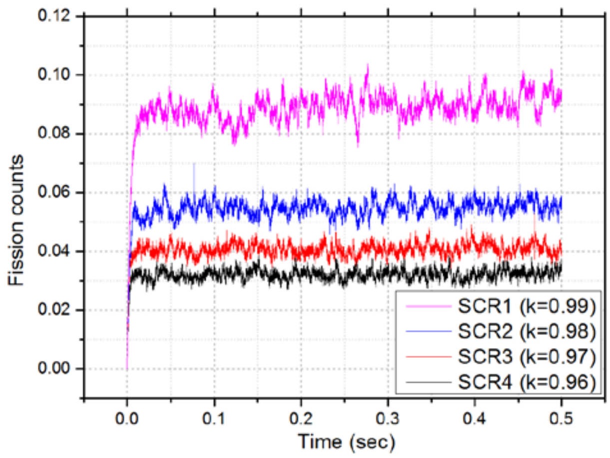

Fig. 4. Changes of the fission count tallies as time

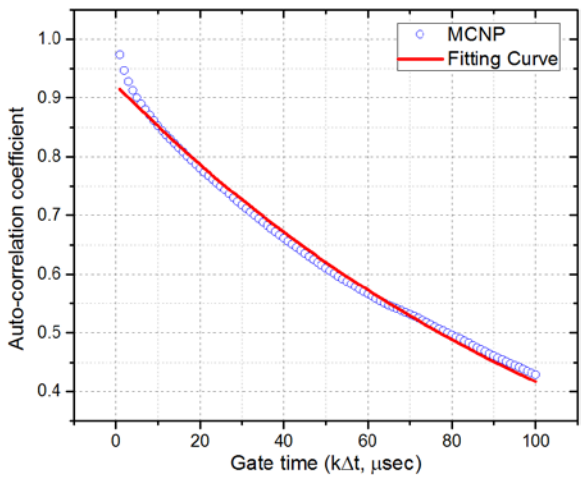

Fig. 5. Fitting curve of Rossi-alpha method in case of SCR4

Table II. Comparison of the multiplication factors obtained with MCNP6 (k-code mode) and Rossi-alpha method

Condition	k_{eff}	$k_{estimated}$	k_{eff} - k_{est} (pcm)
SCR1	0.99069	0.99103	-34
SCR2	0.98010	0.98027	-17
SCR3	0.96970	0.96936	34
SCR4	0.95896	0.95867	29

5. Conclusion

In this work, we simulated the Rossi-alpha method using MCNP6 for a zero power reactor AGN-201K to estimate sub-criticality measurement. Four different subcritical conditions for AGN-201K are considered to show the feasibility of the sub-criticality measurement simulation for different subcritical levels. The simulation was done with two steps : 1) the estimation of the effective multiplication factors and kinetic parameters using MCNP6 (k-code) and 2) fixed source time-dependent transport calculation using MCNP6 for simulating fission counts. In particular, the weight window technique was applied to the simulation in order to reduce the statistical errors in the fission count tallies and it was critical to improve accuracy of the simulation. The time series of the fission count tallies were utilized in the calculation of the auto-correlation coefficients versus gate time for Rossi-alpha method.

The simulation results showed that the estimated reactivity (or sub-criticality level) using the Rossi-alpha method for all the conditions give very good agreements (less than 35 pcm Δk) with the ones by MCNP6 k-code calculation. In the future, we are planning use of the realistic detector of different type (e.g., He-3 detector) outside the reactor core and different noise analysis methods such as Feynman-alpha method.

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