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Feasibility Study of Recriticality Monitoring by Noise Analysis Method

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1. Introduction

In case of reactivity accidents in nuclear power plants (NPPs), the nuclear reactor must be shutdown and maintained as subcritical state so that there is no more chain fission reaction in the core. In Fukushima Daiichi nuclear accidents, TEPCO's release of the high level measured data of Cl-38 and I-131 on March 25th, 2011 raised a big concern on the recriticality of the reactor core but there was no device installed at the site to tell whether the reactor actually reached a critical condition or not [1]. Unlike Fukushima Daiichi NPPs, most nuclear reactors in Korea is a type of pressurized water reactor (PWR) which is considered safer than boiling water reactors (BWRs) in such conditions as Daiichi accident. Nonetheless, a hypothetical scenario of recriticality in PWR is that 1) loss of coolant in the core, 2) temperature rises and control rod material melts while fuel bundles are intact 3), safety injection of water into the core, and 4) a critical condition is reestablished. This paper presents a feasibility study on the continuous monitoring of subcriticality of the damaged reactor core using noise analysis methods so that if the reactor approaches recriticality, people can get alarms and evacuate out of the accidents.

2. Noise Analysis Methods

2.1 Pulsed Neutron Source

The pulsed neutron source (PNS) method is a technique to measure the rate of change of neutron population over time from the initial population injected into the system at time 0.0, and calculate criticality of the system based on the point kinetics equation [2,3]. With delayed neutron precursors ignored, the behavior of prompt neutron population follows

$$n(t) = n_0 \exp(-\alpha t) \tag{1}$$

where n is the neutron population, $\alpha = \alpha_c(1-\$)$, $\alpha_c = \beta / \Lambda$, β =delayed neutron fraction, Λ =generation time, \$=reactivity in unit of β.

Once the value of α is known from a fitting with measured data, then the multiplication factor of the system can be calculated as

$$k = \frac{1}{1-\$\cdot\beta}. \tag{2}$$

2.2 Rossi-alpha Method

Unlike PNS method, the Ross-alpha method assumes random neutron sources over time and the probability representing auto-correlation of the detector counts in time can be written as follows with consideration of prompt fission chains only [4,5]

$$P(\tau) = F^2\varepsilon^2 + \frac{F\varepsilon^2 D_v(1-\beta)^2}{2(\beta-\rho)\Lambda}\exp(-\alpha\tau) \tag{3}$$

where F is the average fission rate, τ is the time difference between two detecting time points (=t_2-t_1), ε is the detector efficiency, and D_v is the Diven's factor which is 0.7966 for U-235. On the other hand, the auto-correlation of measured detector signals can be processed by Eq. (4), which is supposed to be equivalent to the theoretically derived expression in Eq. (3).

$$P(\tau) = P(k\Delta t) = \frac{1}{N-k}\sum_{i=1}^{N-k} C(i)C(i+k) \tag{4}$$

where τ is the lag time over the detector counts, Δt is the time interval of detector signal counting, k is the number of intervals, N is the total number of intervals, and C is the detector counts. The decay constant, α , can be calculated by fitting the curve obtained by Eq. (4) to the function in Eq. (3).

2.3 Feynman-alpha Method

Like Rossi-alpha method, Feynman-alpha method assumes random neutron sources over time. In order to measure the decay constant, α , Feynman-alpha method uses the fact that the ratio of variance to mean of detector counts follows the following equation [5, 6]:

$$\frac{\overline{M^2}-\bar{M}^2}{\bar{M}} \cong 1 + \frac{\varepsilon D_v(1-\beta)^2}{(\beta-\rho)^2}\left(1-\frac{1-\exp(-\alpha\tau)}{\alpha\tau}\right) = 1 + Y(\tau) \tag{5}$$

where M is the detector counts and is obtained as a function of the detector gate time, τ . The ratio of variance to mean in case of Poisson distribution is unity and the additional term $Y(\tau)$ in the right hand side represents the contribution from fission reactions.

3. Application Results

The Godiva problem consisting of a sphere with U-235 and U-238 was used as a model problem to test the feasibility of noise analysis methods. The radius of sphere is 8.741cm and the density is 18.74 g/cc. Table I summarizes the parameters of the problem.

Table I. Model Problem Parameters

Case	Enrichment	β	Λ	α_c
A	70	6.81E-3	7.63E-9	8.93E+5
B	76	6.77E-3	7.07E-9	9.57E+5
C	85	6.60E-3	6.35E-9	1.04E+6
D	92.5	6.54E-3	5.84E-9	1.12E+6

Monte Carlo simulations with McCARD code [7] were performed for four cases in Table I. The first set of simulations was performed in a McCARD criticality mode to calculate the reference k_{eff} values for each case. In the second set of simulations, the neutron sources were injected into the center of Godiva sphere at time 0.0 second and the McCARD code was run in a real time mode in which the time of each neutron is tracked rather than the conventional batch by batch MC simulation. These simulation data were used for PNS method. In the third set of simulations, the neutron sources were injected into the sphere randomly over the simulation time. These simulation data were analyzed with Ross-alpha and Feynman-alpha method.

2.1 Pulsed Neutron Source Method

Figure 1 shows the result from PNS method applied to the case A. The blue circles represent simulated detector signals. And the red line shows the fitting of the signals to the exponential function. The reference k_{eff} of case A from McCARD criticality calculation is 0.86015 and the estimated k_{eff} from PNS is 0.87521.

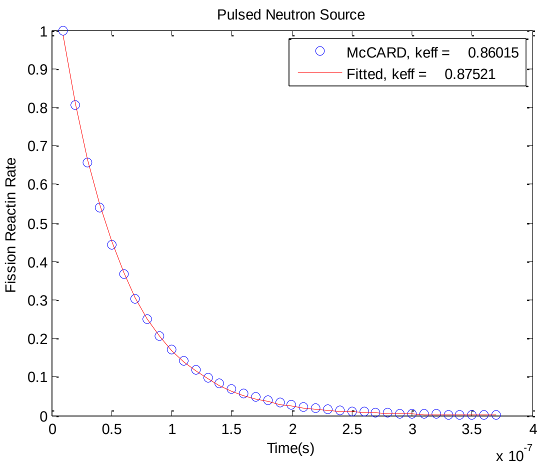

Fig. 1. PNS Method for Case A

3.2 Rossi-alpha Method

Figure 2 shows simulated detector signals of case B to be analyzed by Rossi-alpha method and Feynman-alpha method. The calculated auto-correlation of the data from Figure 2 was plotted in Figure 3 as blue circles. From the red fitted line, k_{eff} was estimated to be 0.92575 whereas the McCARD reference k_{eff} is 0.89735.

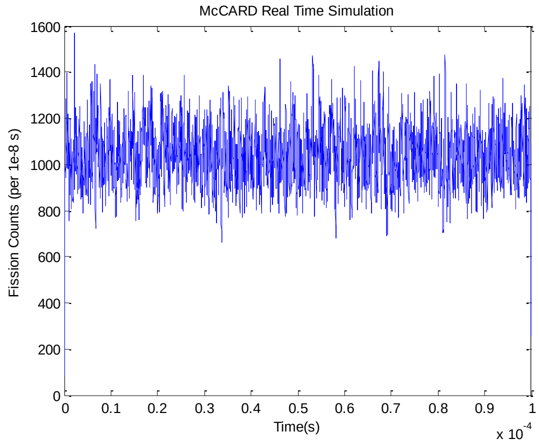

Fig. 2. Simulated Detector Signals in Case B

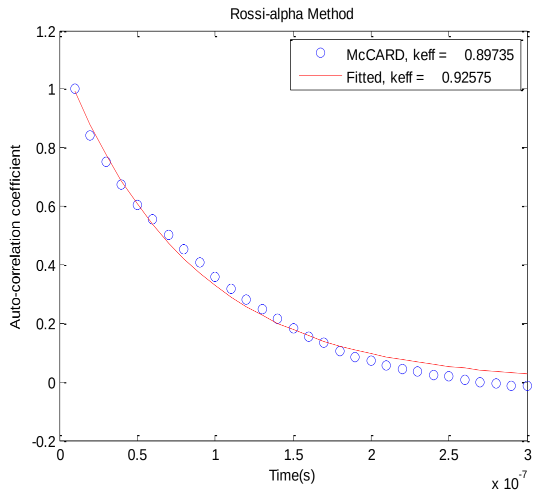

Fig. 3. Rossi-alpha Method for Case B

3.3 Feynman-alpha Method

Figure 4 shows the analysis results for case C using Feynman-alpha method. The blue circles represent the ratio of variance to mean of the detector counts as function of gate times. The estimated k_{eff} from the red fitted line is 0.94759 while the reference k_{eff} from McCARD criticality calculation is 0.94943.

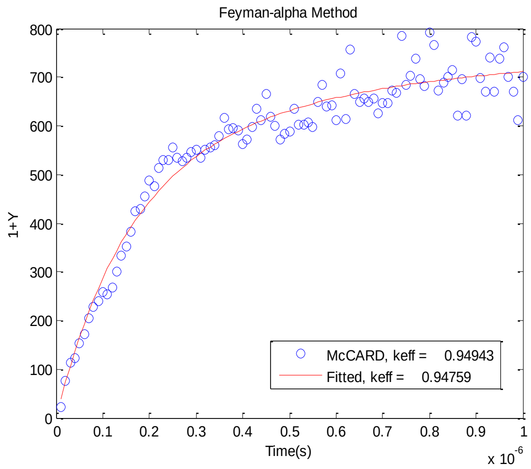

Fig. 4. Feynman-alpha Method for Case C

3.4 Summary of Results

The reference k_{eff} values and the results from noise analysis are summarized in Table II. It is noted that PNS method shows higher accuracy than the other methods. But PNS method cannot be used for continuous monitoring of subcriticality of the reactors. Rossi-alpha and Feynman-alpha methods show similar performance and high accuracy could be obtained for less subcritical states. It is also noted that, as the reference k_{eff} values increase, the estimated k_{eff} values increase.

Table II. Summary of k_{eff} values

Case	Reference	PNS	Rossi-alpha	Feynman-alpha
A	0.86015	0.87521	0.89883	0.90069
B	0.89735	0.90796	0.92575	0.90599
C	0.94943	0.95639	0.96565	0.94759
D	0.98980	0.99619	0.99926	0.99959

4. Conclusions

The analysis in this paper shows that both Rossi-alpha method and Feynman-alpha method can be used for continuous monitoring of recriticality or the approach of reactor core to a critical condition from a subcritical state during the progress of reactor accident. The accuracy of estimated k_{eff}'s improves as the core becomes close to criticality. It looks feasible to detect the approach of the core to recriticality but there are still issues need to be addressed such as the power supply issue to run the PC on which this noise analysis software will be installed in case of station black-out and the quality issue of the detector signals in real NPPs compared with the pure signals generated from Monte Carlo simulation for the analysis in this paper.

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