Subcriticality Monitoring with a Digital Reactivity Meter

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ABSTRACT

The feasibility of subcriticality monitoring by a digital reactivity meter was experimentally investigated using a subcritical assembly. In the experiment, neutron detectors were placed in the reflector region where the subcriticality-weighted neutron flux is almost constant. The significant fluctuation of the neutron signal was filtered with a smoothing and a low-path filter of first order delay. In the subcritical system above with a constant neutron source, it was confirmed through the experiment that a digital reactivity meter with noise filtering module could give real time subcriticality when the detector was placed at appropriate positions. Based on the experiment, we propose that the reactivity meter can be used for monitoring the subcriticality reasonably on the real time basis.

1. INTRODUCTION

There are several methods to estimate subcriticality, such as Feyman-α [1] and neutron noise analysis[2, 3]. However, these methods require analysis of a certain length of time sequence data to estimate the subcriticality using complicated statistical theory. On the other hand, conventional digital reactivity meter can continuously give real time reactivity that is based on the point reactor kinetics equations[4]. It can monitor the reactivity even under transient conditions.

We tried to show the applicability of a digital reactivity meter to subcriticality monitoring. But a digital reactivity meter based on the point reactor kinetics equations is not used in the subcritical system because the neutron flux distributions change with the subcriticality. The other problems are that: (a) the fluctuation of the neutron signal measured in subcritical system is quite large because the neutron flux level is quite low, (b) it is necessary to know the accurate neutron source strength in order to solve inverse kinetics equations, but it is difficult to be done. The solutions for these problems have been studied analytically[5]. In this paper we verify the solutions experimentally in a critical assembly.

2. BASIC CONCEPT

The point reactor kinetics equations are expressed as

$$\frac{dn}{dt} = \frac{(1-\beta)k_{eff}-1}{\ell} n + \sum_{i=1}^{6} \lambda_i C_i + S \,, \tag{1}$$

$$\frac{dC_i}{dt} = \frac{\beta_i k_{eff}}{\ell} n - \lambda_i C_i \quad (i = 1, 2, \cdots, 6) \,, \tag{2}$$

where notations are standard. At a steady state, the following relation is derived.

$$(1 - k_{eff}) n = \ell S = const \,. \tag{3}$$

This implies that if we can find the position where this relation holds in the target subcritical system, the reactivity meter can calculate the corresponding subcriticality, ρ_{sub}, as

$$1 - k_{eff} = (1 - k_{eff,0}) \frac{n_0}{n} \;\rightarrow\; \rho_{sub} \equiv -\rho = -\frac{k_{eff}-1}{k_{eff}} \,, \tag{4}$$

where n_0 and $k_{eff,0}$ are the value of detector signal and that of effective multiplication factor at the initial steady state, respectively. In other words, we can evaluate the effective neutron source strength as

$$S = \frac{(1 - k_{eff,0}) n_0}{\ell} \,, \tag{5}$$

and we can solve inverse kinetics equations.

We define the neutron signal multiplied by the difference of the multiplication factor from one, $(1 - k_{eff})\phi$, as “Normalized Flux”.

From the preliminary numerical simulations, we could find the position where the normalized flux becomes almost constant. In order to verify these results, we carried out an experiment. The objectives are as follows.

a) Comparison of the normalized flux distributions calculated by numerical simulation and those obtained by the experiment.

b) Validation of the concept of subcriticality monitoring.

3. NUMERICAL SIMULATIONS

The experiment was carried out using a subcritical assembly (C45G0 (5 rows)) constructed at Kyoto University Critical Assembly (KUCA) of Research Reactor Institute, Kyoto University[6]. Figure 1 shows the schematic view of the horizontal cross section of KUCA. The core size is 35.5cm wide, 28.4cm long, and 57.0cm high with water reflector. Four BF_3 detectors are placed in the reflector region. The subcriticality was adjusted by removing fuel plates from the core or changing the water level. We can continuously change the subcriticality by changing the water level.

Figure 2 shows the normalized thermal group neutron fluxes calculated by using SRAC-CITATION[7] at the detector positions shown in Figure 1. Note that the same colored lines denote the same number of fuel plates and line types denote water levels. The numbers in Figure 2 denote the detector positions corresponding to those shown in Figure 1. From these numerical simulations, we can find that the normalized flux becomes approximately constant (i.e. Eq.(3) approximately holds) in some places, depending on how the subcriticality of the system has changed. In this experiment, the normalized flux at the most appropriate detector position deviates from the constant by 20%

including the cases for water level changes, the deviation of which is considered to be the major cause of the error in the estimated subcriticality.

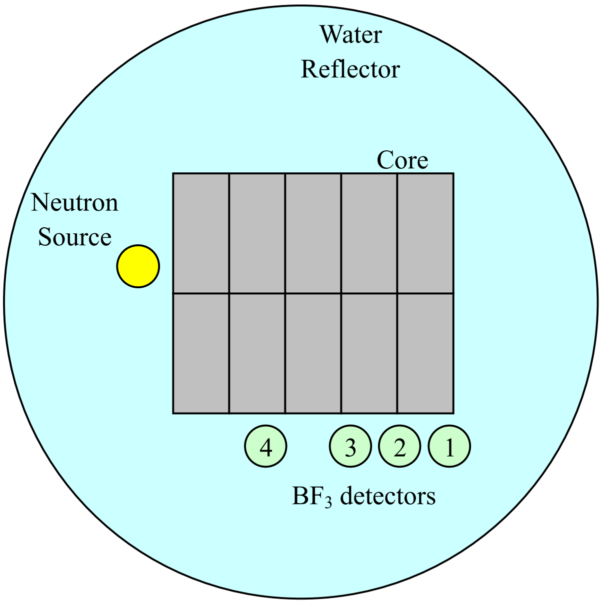

Fig.1 : Schematic view of the cross section of KUCA

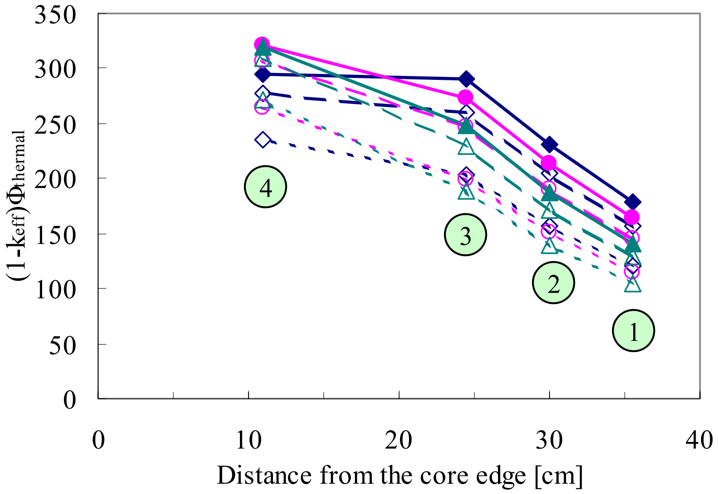

Fig.2 : Normalized thermal group flux distribution calculated by using SRAC-CITATION

4. EXPERIMENTAL RESULTS

4.1 RESULTS OF SUBCRITICALITY CHANGE

Table 1 shows the stable neutron signals of BF_3 detectors that are obtained by the experiments. Reference subcriticalities calculated by using SRAC-CITATION are also shown.

Table 1 : Neutron signals

Fuel plates	Water level [mm]	Neutron signal [cps]				Reference subcriticality [$\%\Delta k/k$]
		BF_3#1	BF_3#2	BF_3#3	BF_3#4	
310	1500.4	906.9	1288.9	1533.1	1718.3	1.47
	1295.8	525.7	754.3	900.2	1040.4	3.05
	1217.0	234.8	341.2	411.9	515.7	5.49
290	1501.2	153.7	222.4	272.4	378.4	6.50
	1291.9	131.3	191.1	236.1	336.8	8.27
	1215.2	90.9	132.9	168.6	257.0	10.78
270	1501.7	87.4	129.2	163.9	255.4	10.40
	1296.9	78.7	116.0	149.3	239.3	12.01
	1217.8	59.6	89.0	115.9	197.9	14.72

In order to estimate subcriticality, we set the initial value of effective multiplication factor for the deepest reference subcriticality as

$$\rho_{sub,0} = 14.72[\%\Delta k/k] \;\rightarrow\; k_{eff,0} = \frac{1}{1+\rho_{sub,0}} = \frac{1}{1+0.1472} = 0.872\,. \tag{6}$$

From Eq.(4), when we use the neutron signal of BF_3#4, for example, the subcriticality that the fuel plates are 310 and water level is 1500.4[mm] is calculated as

$$k_{eff} = 1-(1-k_{eff,0})\frac{n_0}{n} = 1-(1-0.872)\frac{197.9}{1718.3} = 0.9852\,, \tag{7}$$

and then,

$$\rho_{sub} = \frac{1-k_{eff}}{k_{eff}} = \frac{1-0.9852}{0.9852} = 1.50[\%\Delta k/k]\,. \tag{8}$$

Table 2 shows the estimated subcriticalities using the neutron signals of BF_3#4 of which the variation of the normalized flux is the minimum as shown in Figure 2. Errors between the reference subcriticality and the estimated subcriticality are also shown. The difference between the reference and estimated subcriticality is within $0.69\%\Delta k/k$.

Table 2 : Experimental results and errors

Reference subcriticality [$\%\Delta k/k$]	Estimated subcriticality [$\%\Delta k/k$]	Absolute error [$\%\Delta k/k$]
1.47	1.50	0.03
3.05	2.50	-0.55
5.49	5.18	-0.31
6.50	7.19	0.69
8.27	8.16	-0.11
10.78	10.97	0.19
10.40	11.04	0.64
12.01	11.87	-0.14
14.72	14.72	0

Figure 3 shows the reference subcriticalities and the estimated subcriticalities listed in Table 2. In Figure 3, when the points of the estimated subcriticalities are on the line of 45 degree, it is said that we can estimate subcriticalities without errors. As expected from the numerical simulations in Figure

2, the estimated subcriticalities deviate from the reference ones; however, the deviation is considered to be sufficiently small for subcriticality monitoring.

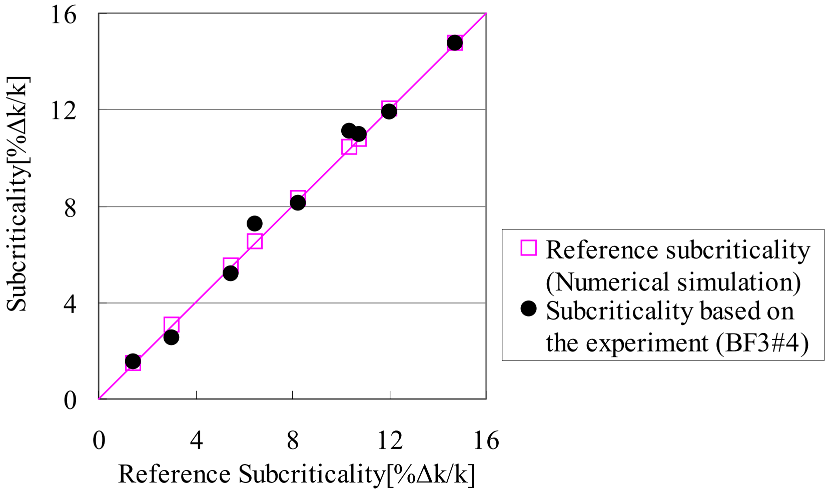

Fig.3 : Reference subcriticality and the experimental results

4.2 RESULTS OF WATER LEVEL CHANGE

Figure 4 shows the estimated subcriticality by a digital reactivity meter when the water level was continuously changed. In Figure 4, the subcriticality fluctuates because the neutron signals fluctuate around the average. Figure 5 shows the estimated subcriticality after the fluctuation of neutron signal was filtered with a smoothing and a low-path filter of first order delay. As shown in Fig.5, such fluctuation could be sufficiently reduced by filtering the neutron signal fluctuation by the filter described above. The broken lines in Figure 5 show the reference subcriticality at the steady state calculated by using SRAC-CITATION. The difference between the reference and estimated subcriticality is due to the change of the normalized flux at the detector position as shown in Fig.2, which is caused by the water level change.

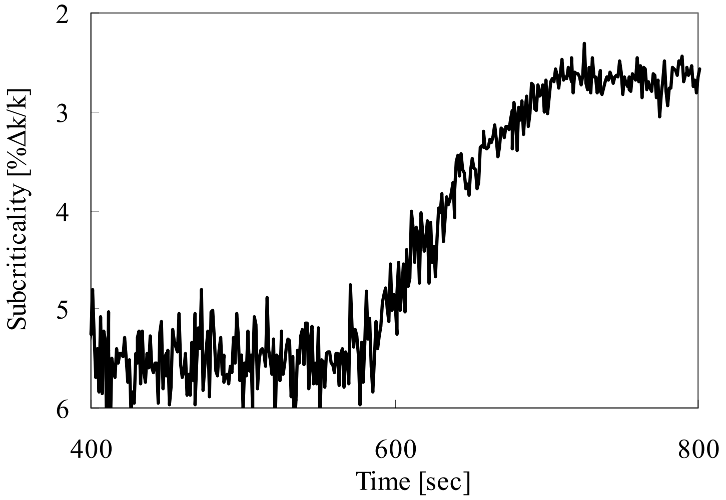

Fig.4 : The subcriticality estimated by a digital reactivity meter when water level is changed (Sampling time = 1 [sec], Filter time constant = 0 [sec])

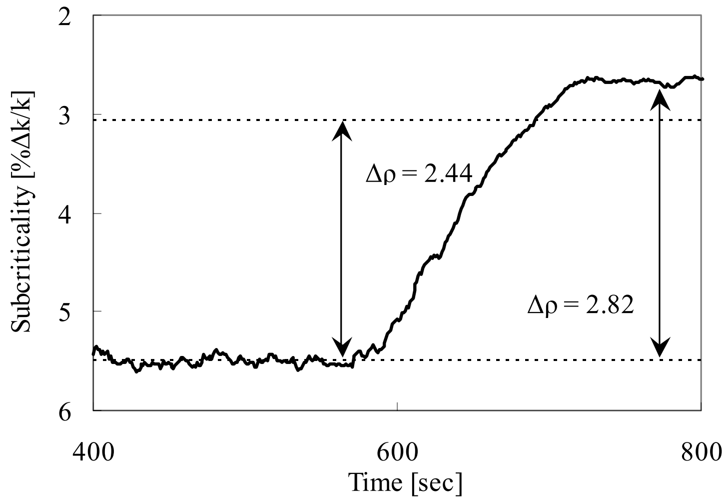

Fig.5 : The subcriticality estimated by a digital reactivity meter when water level is changed (Sampling time = 1 [sec], Filter time constant = 10 [sec])

4.3 SENSITIVITY OF DETECTOR POSITION

As the deviation of normalized flux from constant depends on the detector position as shown in Fig.2, the error in the estimated subcriticality depends on detector position as shown in Table 2.

Figure 6 shows examples of the estimated subcriticalities by using detector signals of different positions. As shown in Fig.6, the values of the estimated subcriticalities depend on the detector positions. By selecting proper detector position, we could obtain conservative estimations of subcriticality.

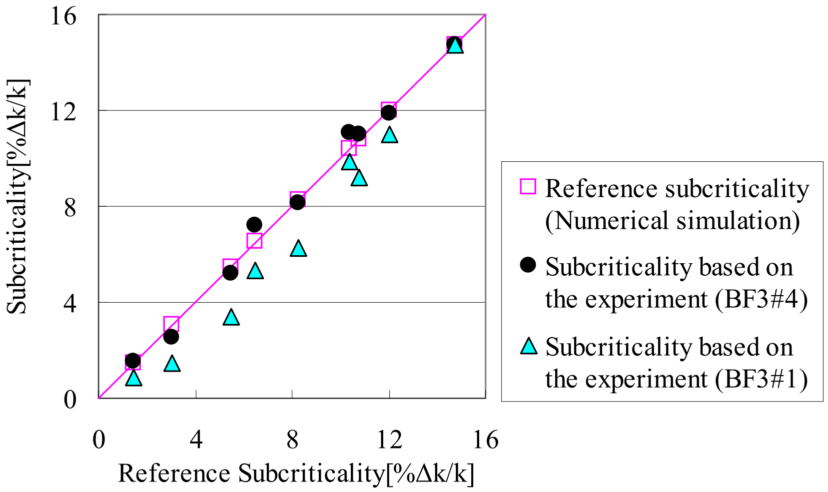

Fig.6 : Sensitivity of detector position to subcriticality

CONCLUSION AND PROPOSAL

When the detector is placed at appropriate positions, we confirmed that a digital reactivity meter with noise filtering module could estimate the real time subcriticality. The subcriticality estimated by the digital reactivity meter could be sufficiently applied for subcriticality monitoring when the detector position is appropriately chosen. The error in the estimated subcriticality could be further reduced by performing more detail numerical calculation for the determination of appropriate detector position, and also by introduction of spatial correction factors.

Based on the above study, we propose that a digital reactivity meter can be used as a subcriticality monitor.

ACKNOWLEDGEMENTS

This work has been carried out in part under the Visiting Researcher’s Program of the Research Reactor Institute, Kyoto University.

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