SUBCRITICALITY ESTIMATION BY VIRTUAL NEUTRON CAPTURE METHOD

Takeshi Mitsuyasu^{1,2} and Yuichi Morimoto^{1,2}

¹International Research Institute for Nuclear Decommissioning
5F, 3 Toyokaiji Building, 2-23-1 Nishi-Shimbashi, Minato-ku, Tokyo 105-0003, Japan

²Hitachi GE Nuclear Energy, Ltd.
1-1, 3-chome, Saiwai-cho, Hitachi-shi, Ibaraki-ken, 317-0073, Japan

takeshi.mitsuyasu.mz@hitachi.com, yuichi.morimoto.fb@hitachi.com

ABSTRACT

The criticality safety control technique is required for the fuel debris removal from the Fukushima Dai-Ichi Nuclear Power Station which experienced a severe accident. The subcriticality estimation is expected to be done with only limited information about the fuel debris while the primary containment vessel internal survey work is ongoing. The purpose of this study is to develop the subcriticality estimation method called the virtual neutron capture method. The neutrons from the surface of the fuel debris represent a major portion of detector counts. The method consists of two evaluations: the evaluation at the surface of the fuel debris for which the isotope compositions are known by fuel debris sampling and the evaluation at the region of the fuel debris for which these compositions are unknown. For the unknown composition region, the average isotope composition with arbitrary water content is given. The method surveys the relationship with the detector count and the neutron multiplication factor with any size of the unknown composition region and any ratio of the water content before the on-site evaluation. The method is verified by experiments done in the Kyoto University Critical Assembly. The method shows that the maximum difference from the reference neutron multiplication factor is 4.5 %dk. As a result, the virtual neutron capture method can be adopted to the subcriticality monitoring if the method includes the estimation margin of 4.5 %dk within the neutron multiplication factor range from 0.70 to 0.95.

KEYWORDS: Fukushima Dai-Ichi Nuclear Power Station, debris, criticality safety, subcritical, virtual neutron capture

1. INTRODUCTION

The criticality safety control technique is required for the fuel debris removal from the Fukushima Dai-Ichi Nuclear Power Station which experienced a severe accident. One of the criticality safety control techniques is the subcriticality monitoring by a subcriticality estimation method. Several subcriticality estimation methods have been proposed. Two examples are the neutron source multiplication method (NSM) [1] and the Feynman- α method which is known as a stochastic method [2]. In this study, the developed method is based on the NSM method because the detector count is time-averaged value, not stochastic. The NSM method is explained using the following formula:

$$C = \varepsilon(S + kS + k^2S + \dots) = \frac{\varepsilon S}{1-k}, \quad (1)$$

where C is the neutron count rate obtained from a neutron detector, ε is the detector efficiency of the neutron detector, S is the intensity of an external neutron source and k is the neutron multiplication factor of a subcritical system. To estimate the subcriticality using the detector count, the detector efficiency of the neutron detector and the intensity of an external neutron source are necessary. The NSM method is based on the point reactor approximation, ε and S are evaluated by averaging ε and S in the whole system obtained using detailed 3D calculations. However, the information of the whole system including the position and the isotope composition of the fuel debris in the Fukushima Dai-Ichi Nuclear Power Station are only partially available, most information is unavailable. For this reason, internal survey work in the primary containment vessel is ongoing. The internal survey by fuel debris sampling is expected to identify the form and the isotope composition at the surface of the fuel debris. The subcriticality estimation methods are expected to be used with limited information about the fuel debris. The purpose of this study is to develop a subcriticality estimation method, called the virtual neutron capture (VNC) method, using limited information consisting of the position of the fuel debris and the isotope composition at the surface of the fuel debris.

2. METHODOLOGY OF THE VNC METHOD

2.1. Theory of the VNC Method

The information at the surface of the fuel debris can be expected to be obtained from fuel debris sampling. The system of the fuel debris can be simplified to Fig. 1. There are two regions, the region of known debris composition with the neutron source intensity S_1 and the region of unknown debris composition with the neutron source intensity S_2 . The neutron detector is placed in the neighborhood of the known debris region.

Figure 1. Schematic Drawing of Debris and a Detector.

In the NSM method, if the neutron multiplication factor is zero, the detector count is given as below:

$$C_v = \varepsilon S, \quad (2)$$

where C_v is the detector count if the number of produced neutrons per fission reaction ν is zero or the fission reaction is replaced by the capture reaction. This is the virtual reaction. The detector count C_v , however, can be evaluated by calculation methods such as a Monte Carlo method if the parameter ν is zero. In this condition, the detector count C_v has little influence from the unknown composition region because the neutrons produced in this unknown region have to go through the known composition region.

The neutrons from the surface of the fuel debris represent a major portion of the detector counts. Equation (2) can be rewritten as:

$$C_v \cong \varepsilon_1 S_1, \quad (3)$$

where ε_1 is the detector efficiency of the neutron detector in terms of the neutrons from the known region. The detector efficiency weakly depends on the unknown region because most neutrons produced in the known region go directly to the detector but a few neutrons go to the unknown region and are reflected, and go to the neutron detector. Then, equation (1) can be rewritten by using equation (3).

$$k = 1 - \frac{C_v}{C}. \quad (4)$$

The neutron source intensity in the known region is given by the fuel debris sampling.

2.2. Procedure of the VNC Method

The procedure of the VNC method is shown in Fig. 2. The procedure is divided into two stages. The first stage is the evaluation in advance, and the second stage is the on-site evaluation.

In the first stage, the information about the debris surface form and the material composition is obtained from the internal survey work such as the surveys by an optical camera, ultrasonography and sampling. The information defines the known composition region. And, the detector position is set to the known region. The unknown region is replaced by the virtual region. The virtual region is assumed so that the region size (a) and the water content (b) are parameters. For example, the size of the virtual region is defined as system A, system B and system C which are illustrated in Fig. 2. The water content within the virtual region is defined as from 0 % to 100 %. If the water content is 50 %, fuel debris of 50 % is included. The isotope composition of the fuel debris in the virtual region is defined to be the representative composition. The parameters (a) and (b) are numerically surveyed as parameters by the calculation. There are two kinds of calculation. The first kind is the normal calculation which evaluates the detector count C , and the second kind is the virtual neutron capture calculation which evaluates the detector count with the condition of the virtual neutron capture C_v . The data groups obtained from the surveys are smoothed by the fitting curve of the relationship between the neutron multiplication factor and the detector count.

In the second stage, the detector count is measured on-site and the neutron multiplication factor is evaluated from the fitting curve calculated above.

Figure 2. Procedure for the VNC Method.

3. EXPERIMENTS AND NUMERICAL RESULTS

3.1. Subcritical Experiments in Kyoto University Critical Assembly

The subcritical experiments were performed in the Kyoto University Critical Assembly (KUCA). The B core of KUCA is the solid moderated core. The core has 5.08 cm x 5.08 cm cells into which the solid moderator can be inserted and the fuel is slab shape. The core fuel is the excessive moderation type because the H/U value in fuel region is 8 which is greater than the standard BWR value 4. The fuel cell is shown in Fig. 3. Polyethylene is used for the solid moderator. The three cases of KUCA experiments are shown in Table I. The difference in the cases is the number of fuel cells, and the difference cause the discrepancy of k effective (k_{eff}). k_{eff} is set from 0.70 to 0.95. The core configurations of the experiments are shown in Figs. 4 and 5. All the control rods and the safety rods are withdrawn. None of the fuel cells include a neutron source. The neutron source of the experiments is externally given as an Am-Be cell.

Figure 3. Fuel Cell of Excessive Moderation (P38P32EU Fuel).

Table I Experimental cases in KUCA.

No.	Experiment case	Core configuration	
		No. of fuel cells	Figures
1	Excessive moderation ($k_{eff} \approx 0.95$)	P38P32EU x 19	See Fig. 4
2	Excessive moderation ($k_{eff} \approx 0.80$)	P38P32EU x 11	See Fig. 5 (Left)
3	Excessive moderation ($k_{eff} \approx 0.70$)	P38P32EU x 8	See Fig. 5 (Right)

Figure 4. Core Configuration No.1.

Figure 5. Core Configurations No.2 (Left) and No.3 (Right).

3.2. Evaluation of the Neutron Multiplication Factor by the VNC Method

The calculation code used for the VNC method was MVP version 3 [3] with the nuclear data library JENDL-4.0 [4]. The cells of the control rods and the safety rods are considered as the void cells because these rods are withdrawn. The neutron detector used for the calculation is the number 15 cell. The neutron detectors in the number 11 and 14 cells are not used. The detector count in the calculation is defined as the capture reactions of boron within the neutron detector because the calculation code cannot simulate the electronic signals in the neutron detector. The detector count bias between the experiment and the calculation is evaluated in another experimental case. In this study, all results are corrected by using the bias.

The known composition region is only for one fuel cell next to the neutron detector 15. An example of the virtual system of the core configuration No.1 is shown in Fig. 6. The letters in the virtual area mean the region size. Fig. 6 shows the “F” size. Other examples of the “A” size and “D” size are shown in Fig. 7. A survey of the size of the virtual region is performed from size “A” to size “F”. The water content is changed in each size. The Monte Carlo calculation is performed to evaluate C and C_v . The relationship between the detector count and the neutron multiplication factor is evaluated by equation (4). The virtual system for the experimental cases Nos.1 to 3 is the same because the known region is the same in experimental cases Nos.1 to 3,. Thus, the relationship can be used for experimental cases Nos.1, 2 and 3.

2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	A	B	C	F	3	3	2	2	2
2	2	2				E	3	3	3	10	2
2	2	15	23			D	3	3	2	2	2
2	2	2				E	3	3	2	2	2
2	2	2	A	B	C	F	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2

ID	Description
23	Fuel (Excessive moderation)
2	Polyethylene
3	Void
10	AmBe neutron source
15	Detector
	Virtual area

Figure 6. System for the VNC Method in Case No.1.

2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	A	3	3	3	3	3	2	2	2
2	2	2				3	3	3	3	10	2
2	2	15	23			3	3	3	2	2	2
2	2	2				3	3	3	2	2	2
2	2	2	A	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2

2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	A	B	C	3	3	3	2	2	2
2	2	2				3	3	3	3	10	2
2	2	15	23			D	3	3	2	2	2
2	2	2				3	3	3	2	2	2
2	2	2	A	B	C	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2
2	2	2	3	3	3	3	3	3	2	2	2

Figure 7. Examples of the Virtual System (Left: Size “A”, Right: Size “D”).

The plotted points of the relationship between the detector count and the neutron multiplication factor are shown in Fig. 8. The letters “A” to “F” in the explanatory notes indicate the size of the virtual region. The plotted points have some variation. The fitting line is evaluated at the least square difference between the fitting line and the plotted data. The calculation data and the fitting line are shown in Fig. 9. The figure also shows the detector count obtained in the experimental cases Nos.1, 2 and 3. Then, the neutron multiplication factor in experiment Nos. 1, 2 and 3 is obtained by the VNC method. The results and the comparison with the reference k effective are shown in Table II. The value of the “estimation of VNC method” is obtained from the fitting line in Fig.9. The maximum difference from the reference neutron multiplication factor is 4.5 %dk.

Figure 8. Results of VNC Method in Case Nos.1-3.

Figure 9. Fitting Line and Detector Count for KUCA Experiments, Case Nos.1-3.

Table II. Estimation of neutron multiplication factor.

Case No.	Reference neutron multiplication factor	Estimation of VNC method	Difference (%dk)
1	0.952	0.966	+1.5
2	0.807	0.825	+1.8
3	0.690	0.733	+4.3

4. CONCLUSIONS

A subcriticality estimation method, which is called the virtual neutron capture method, was proposed using only limited information consisting of the position of the fuel debris and the isotope composition at the surface of the fuel debris. The virtual neutron capture method is based on the neutron source multiplication method, and it utilizes the fact that the neutrons from the surface of the fuel debris represent a major portion of the detector counts. The method surveys the relationship with the detector count and the neutron multiplication factor with any size of the unknown isotope composition region and any ratio of the water content before the on-site evaluation. The method was verified in experiments done in the Kyoto University Critical Assembly. The k effective of the core was from 0.70 to 0.95. The maximum difference from the reference neutron multiplication factor was 4.5 %dk. As a result, it was concluded the virtual neutron capture method can be adopted to the subcriticality monitoring if the method includes the estimation margin of 4.5 %dk within the neutron multiplication factor range from 0.70 to 0.95.

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