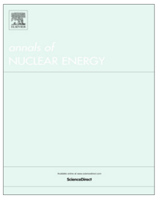
Annals of Nuclear Energy 85 (2015) 78–92

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Application of the "best representativity" method to a PWR fuel calculation using the critical experiments at the Toshiba NCA facility

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ARTICLE INFO

Article history:
Received 22 October 2014
Received in revised form 17 April 2015
Accepted 18 April 2015

Keywords:
Representativity factor
Critical experiment
LWR
Infinite neutron multiplication factor
Toshiba NCA facility
PWR simulation

ABSTRACT

To judge the applicability of a critical experiment, it is necessary to confirm the similarities of the experiment with actual reactor conditions or equipment. The concept of the "representativity factor" has been well adopted since the late 1970's, particularly for fast breeder reactors (FBRs) and future reactor studies. In our previous study, we extended this concept to the design of a light water reactor (LWR) system, and derived mathematical formulas for a new numerical evaluation method to correct a physical property of a target system. This method is different from the cross-section adjustment method and the bias factor method. For the first qualification of the method, sample calculations were carried out to correct the effective neutron multiplication factor through critical experiments at the Toshiba Nuclear Critical Assembly (NCA) facility.

We also compared the result with that of the Product of Exponentiated experimental values method (PE method) of the extended bias factor methods. A good agreement was observed.

The purpose of this study was to demonstrate the applicability of the method to the infinite neutron multiplication factor. Using the method and three kinds of critical experiments of NCA, calculations were performed to correct the infinite neutron multiplication factor of a pressurized water reactor (PWR) fuel assembly. Under combination of NCA critical experiments, the representativity factor became closer to unity. Simultaneously, a correction of the infinite multiplication factor was realized. Results were firstly compared among different combinations of experiments. Comparisons with the results of other calculation methods were also conducted. Whole results were explained with physical considerations.

1. Introduction

For current nuclear calculations of light water reactors (LWRs), two-step calculations are widely carried out using a combination of a lattice physics code and a three-dimensional core simulator. The former is adopted for fuel assembly calculations, while the latter is used for the thermal and nuclear coupling calculations of the whole reactor.

To increase safety margins and improve the economic performances of LWRs, the most reliable calculations are always required. Consequently, validation of the quality of lattice physics codes is highly important before design calculations.

Nuclear critical experiments have been widely used to validate and improve the quality of lattice physics codes since the inception of the nuclear industry.

The most common physical property obtained by a critical experiment is critical mass which can be treated as the effective neutron multiplication factor (the critical eigenvalue). However, lattice physics codes are fundamentally designed to provide the infinite neutron multiplication factor. Then, these two values do not share the completely same physical meaning and therefore cannot be compared directly. It is thus necessary to obtain from a critical experiment a suitable physical property that can be used to make a direct comparison or to produce good feedback for the lattice physics code.

In addition, the design of a fuel assembly for any LWR is specific. Thereby, a critical experiment should be quantitatively evaluated under recognizing how similar it is to the target fuel assembly.

Generally, in terms of theoretical treatments of the measurement values of critical experiments, the cross-section adjustment method and the bias factor method have been conventionally adopted (Dragt et al., 1977; Kugo et al., 2007; Kuroi and Mitani, 1975; Matthes, 1979; Sano and Takeda, 2006). These two methods are widely used for fast breeder reactor (FBR) studies.

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http://dx.doi.org/10.1016/j.anucene.2015.04.026
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In a LWR, the shape of the thermal neutron spectrum is complicated and changeable, along with locations and operating conditions. Moreover, the multi group type-standard cross section library cannot be seen. For these reasons, calculation procedures of a cross-section adjustment are not as suited to LWRs.

The bias factor method can be applied for a LWR study. Currently, however, during calculation procedures, this method does not seem to provide a simple numerical value for judging feasibility of critical experiments easily.

Thereby, these two methods do not seem to be an optimal choice for the application to a LWR study.

In our previous study (Umano et al., 2014), aiming at an application to a LWR study, a new calculation method was proposed under the concept of "best representativity" (Aliberti et al., 2006; Broadhead et al., 2004; Elam and Rearden, 2003; Gandini, 1988; Palmiotti et al., 2007, 2009; Palmiotti and Salvatores, 2011; Rearden et al., 2011; Williams, 2007).

This method combines the information provided by calculation results and experimental results using sensitivity coefficients and a covariance matrix.

By using this method, it is possible to achieve the best utilization of the experimental information as its linear combination. It might be possible to apply this method to a FBR study. However, the authors do not expect such a usage. In the field of FBR, the neutron spectrum of an experiment is generally quite similar to that of a target system. Consequently, we do not have to pay much attention to the representativity. Furthermore, the cross-section adjustment method and the bias factor method are highly applicable.

In our study, the most distinguished point of this method is not to use a large number of experimental information. Since good amounts of human labor and resources including financial cost are always required for performing critical experiments, the number and the content of experiments should be deeply considered and should be well designed. In order to save total costs for performing critical experiments, moreover not to increase the uncertainty of the corrected value caused by the combination of various uncertainties, adequate maximum experiment case number could be six or so. Therefore, the worth of each experiment to the target system should be evaluated quantitatively.

This combination is carried out under the condition of maximizing the representativity factor of experiments to be newly defined (Umano et al., 2010, 2014). Therefore, we can judge the applicability of combined critical experiments to a target system according to the new representativity factor.

Recently, the representativity factor concerned with multi-physical properties has been proposed for the design of a critical experiment (Blaise et al., 2012; Dos Santos et al., 2013).

However, the one of the purposes of this study is to show a correction method of a particular physical property. Therefore, at the moment, the only one physical property, the neutron multiplication factor for example, can be combined. Consequently, both information of fission rate distributions and the neutron multiplication factor cannot be combined since the concept of this method is not "variance reduction." This is a disadvantage of the method. This disadvantage should be improved in further study.

In the previous study, the mathematical formulas were derived and sample calculations were performed (Umano et al., 2014). For the first qualification, the method was applied to the effective neutron multiplication factor of a pressurized water reactor (PWR) type critical experiment at the Toshiba NCA facility. The Standardized Computer Analyses for Licensing Evaluation (*SCALE*) 5.1 system was utilized (SCALE ORNL/TM-2005/39, 2006; Umano et al., 2014). The result was compared with that of PE method of the extended bias factor methods (Kugo et al., 2007). A good agreement between two results was observed.

The initial purpose of this study was to certify the applicability of the proposed method to the infinite neutron multiplication factor. The second purpose of this study was to see the performance of the method with using three experiments, since the number of combined experiment case was merely two in the former study. The third purpose of this study was to define a calculation factor for clarifying the difference from regression analysis or variance reduction procedures. In addition, a different calculation factor was also proposed to contribute to improve reliability.

The proposed method was applied to a PWR 17 × 17 fuel assembly calculation. Using this method, the infinite neutron multiplication factor of the PWR fuel assembly was corrected by combining the three results of NCA critical experiments.

The validity of the calculation results were shown after comparing the results of different combined experiment cases. Whole results were discussed with physical explanations.

2. Calculation method of the present study

In the present study, the calculation method described in the previous study was applied (Umano et al., 2014). (See Appendix 1 for details.)

2.1. A definition of the squared difference ratio (SDR) and a proposal of the reliability correction factor (RCF)

As already mentioned in the previous study, the calculation method is not a regression analysis, not a variance reduction method, either. In this section, the squared difference ratio is defined to show the characteristics of the method. In addition, the reliability correction factor is newly proposed to contribute to increase reliability. They can be additionally applied to the calculation method. These two values are related to the representativity factor (*RF*) under combinations. Consequently, hereinafter, *RF* is considered to be greater than or equal to null.

Regarding the relation between *RF* and a variance reduction of calculation values for a target system, it is often taken for granted that the variance reduction rate is proportional to $(1 - RF^2)$. In statistics, *RF* can normally be regarded as the correlation coefficient r, and the square of this factor, r^2, is called the coefficient of determination that is often used in regression analysis or in the least-squares fitting. The coefficient of determination is calculated for a regression line, and the sum of squared residuals (SSR) is expressed as follows:

$$\mathrm{SSR} = SS_{yy}(1 - r^2) \tag{1}$$

(See Appendix 2 for details.) Based on Eq. (1), it is often understood that the variance reduction rate is proportional to $(1 - RF^2)$. But we should know that this relation is merely adequate for a method that makes use of regression analysis or the least-squares fitting.

The objective of the new calculation method described in the previous study was not to obtain a regression line under the condition of using many numbers of data. Thereby, the reduction rate of error evaluation should be newly defined for this method in a different way from other methods.

In this section, all mathematical notations are same as those of the previous study. (See Appendix 1 for details.)

Let S_i, S_R and W to be a sensitivity coefficient vector of the experiment i $(i = 1, 2, \cdots, n)$, that of the target system and a covariance matrix, respectively. They are all concerned with the same physical property and calculation parameters. In pure mathematical derivations, the definitions of S_i, S_R and W are not particularly limited as for a physical property. In this study however, they are all assumed to be concerned with a nuclear data library.