Annals of Nuclear Energy 105 (2017) 311–328

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Improvement of the "best representativity" method toward an industrial application

Takuya Umano [a,*], Kenichi Yoshioka [a], Toru Obara [b]

[a] Toshiba Corporation, Energy Systems & Solutions Company, 8, Shinsugita-cho, Isogo-ku, Yokohama-shi 235-8523, Japan
[b] Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1-N1-19, Ookayama, Meguro-ku, Tokyo 152-8550, Japan

ARTICLE INFO

Article history:
Received 12 May 2016
Received in revised form 2 March 2017
Accepted 3 March 2017

Keywords:
Sensitivity coefficient
Covariance file
Representativity factor
Critical experiment
LWR
Neutron multiplication factor
Toshiba NCA
ICSBEP data disk
SCALE 6.1.2

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. We extended this concept to the design of a light water reactor (LWR) system. In the first study, a new numerical evaluation method and a calculation system were developed and qualified. In the second study, an application calculation was conducted to validate the method. Based on the method, calculations were performed to correct the infinite neutron multiplication factor of a pressurized water reactor fuel assembly with using three kinds of critical experiments. The representativity factor became closer to unity. A correction of the infinite multiplication factor was well achieved.

In this study, for aiming at an industrial application of the method, the method was improved to be more suitable for the single experiment case. In addition, a modification of the calculation procedures was proposed to prevent a very large increase of the final combined uncertainty. Furthermore, to validate the method, calculations were conducted according to ICSBEP 2010 data disk with utilizing critical experiments that were performed at different critical facilities. Simultaneously, with "SCALE 6.1.2" system and "ENDF/B-VII" 238G library, the applicability of the method was studied. All calculation results are shown and 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. Consequently, validation of the quality of lattice physics codes is highly important before design calculations. Therefore, nuclear critical experiments have been widely used to validate and improve the quality of lattice physics codes since the inception of the nuclear industry.

In our first 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; Blaise et al., 2012; Broadhead et al., 2004; Dos Santos et al., 2013, Elam and Rearden, 2003, Gandini, 1988; Palmiotti et al., 2007, 2009, Palmiotti and Salvatores, 2011, Rearden et al., 2011; Williams, 2007).

By using sensitivity coefficients and a covariance matrix, this method combines the information obtained through the relative differences between calculations and experimental results. In other words, this method makes it possible to achieve the best utilization of the experimental information as its linear combination. This combination is carried out under the condition of maximizing the newly defined representativity factor of experiments. Therefore, we can judge the applicability of combined critical experiments to a target system by seeing the new representativity factor. Simultaneously, a calculation value of the target system is corrected by the information of experiments. As a result, validation of the quality of lattice physics codes is promoted.

In the first study, the mathematical formulas were derived and sample calculations were performed. For qualification, the method was first applied to the effective neutron multiplication factor of a pressurized water reactor (PWR) type critical experiment at the Toshiba Nuclear Critical Assembly (NCA) facility (Umano et al., 2014).

* Corresponding author.
E-mail address: takuya.umano@toshiba.co.jp (T. Umano).

http://dx.doi.org/10.1016/j.anucene.2017.03.002
0306-4549/

After the qualification, 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 (Umano et al., 2015). All calculation results seemed to be acceptable and understandable.

This is the third study of the "best represenativity" method. Consequently, the next study should be performed for the industrial application. However, it seemed that there are still some issues to be cleared or solved before such an application. These issues can be:

(1) In the method, the representativity factor to the target system is maximized through making the best linear combination of critical experiments. Liner combination coefficients are determined by the inversion of a matrix of the equation. Therefore, the NS (necessary and sufficient) condition of regularity of the matrix should be clarified to judge the calculation capability/applicability.
(2) Critical experiments generally require a lot of manpower and financial costs. Therefore, a calculation result cannot always expect more than one critical experiment to make comparisons. In the method, as for the single critical experiment case, a linear coefficient is determined simply to equalize the amplitude of the two sensitivity coefficients which respectively belong to a critical experiment and the target system. Further study should be performed.
(3) To determine linear coefficients, the calculation is conducted to maximize the combined representativity factor to the target system as large as possible. After this determination, the error propagation law is adopted for the combination of uncertainties of critical experiments. The uncertainty of a critical experiment itself is not directly related to the determination of linear combination coefficient however, when the measurement uncertainty of a critical experiment is quite larger than other uncertainties, we should reconsider the importance of this critical experiment even though it shows a large representativity factor. In this point, the method should be improved.
(4) So far, in the method, the only one representativity factor concerning a single physical property was manipulated. A new calculation method to manage two and more kinds of representativity factors should be considered.
(5) In the former two studies, the "SCALE 5.1" system was utilized. At the beginning of the year 2016, this is not the latest version of the "SCALE" system. In addition, usable nuclear data library of the latest system is "ENDF/B-VII". The calculation using an updated version of the "SCALE" system is preferable and such a calculation should be performed.
(6) In two previous papers, all example calculations were performed with merely using the results of a critical experiment at the Toshiba NCA facility. A combination of measurement results of different facilities should be tested to clarify the performance of the method.

The purpose of this study is to show a suitable solution or an improvement to each of the above issues. Since issue (1) and issue (4) are mainly related with mathematical manipulations, they are explained in Appendix A and in Appendix C, respectively. In the following chapters, the rest of issues are discussed in detail. An improvement of the method is proposed and qualified. In addition, physical explanations and discussions are presented.

2. The new calculation procedure for n = 1 (the single experiment case)

2.1. A new calculation procedure for a single experiment

Based on the previous study (Umano et al., 2015), the combination of case 2 and case 3 of NCA PWR critical experiments was adequate for the correction of the infinite neutron multiplication factor (k-inf) of the PWR 17 × 17 fuel assembly. This meant that suitable two critical experiments enabled us to perform a good correction. On the other hand, critical experiments require manpower (human resources) and considerable financial costs. In a realistic way of thinking, it is not always possible to perform more than one critical experiment. Moreover, it is often the case that all available information is the result from a single critical experiment.

So far, the calculation procedures of the method do not seem to be good enough for the single experiment case. The reason is apparent when seeing Eqs. (10) and (11) of the previous study (Umano et al., 2014).

In this chapter, to answer this issue, a new study is conducted to improve the calculation procedure for the single experiment case. Hereinafter, n denotes the number of critical experiments utilized in this study. Therefore, for the single experiment case, we represent it as n = 1. In chapter 2, the number of critical experiment to be applied to the calculation is always one.

For n = 1, by Eq. (11) (Umano et al., 2014), a linear combination coefficient α_1 is automatically determined just for satisfying the following relation.

$$\alpha_1 S_1^T W \alpha_1 S_1 = S_R^T W S_R \quad (= d) \quad (T : \text{transpose}) \tag{1}$$

or

$$(\alpha_1)^2 = (S_R^T W S_R)/(S_1^T W S_1) \tag{2}$$

where, S_1 is a sensitivity coefficient vector of an experiment and S_R is a sensitivity coefficient vector of the target system. W is a covariance matrix of the nuclear data library which is applied to the calculation. d is the amplitude.

This is merely an equalizing of the amplitude/length of two vectors. In other words, the proposed method was not completely tactical for the single experiment case. Therefore, the calculation method should be reconsidered. In this chapter, modification and improvement of the method is shown and proposed.

Suppose that S_E is a sensitivity coefficient vector of an experiment system, S_R is a sensitivity coefficient vector of the target system. With applying a covariance matrix W, the Representativity Factor (RF) can be defined as

$$RF = S_E^T W S_R \Big/ \left\{ (S_E^T W S_E)^{1/2} (S_R^T W S_R)^{1/2} \right\} \tag{3}$$

The amplitude of sensitivity coefficient vector S_E and the amplitude of sensitivity coefficient vector S_R are also calculated respectively as

$$a = (S_E^T W S_E)^{1/2} \tag{4}$$

$$b = (S_R^T W S_R)^{1/2} \tag{5}$$

It is understood that these a and b correspond to the length of each sensitivity coefficient vector with the covariance matrix W.

Then, RF is expressed in another form as follows.

$$RF = S_E^T W S_R/(ab) \tag{6}$$

RF can be considered to be *cosine* θ, in which θ is the angle between two sensitivity coefficient vectors S_E and S_R. Therefore it is easily understood,