Annals of Nuclear Energy 109 (2017) 698–704

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

A new cross section adjustment method of removing systematic errors in fast reactors

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ARTICLE INFO

Article history:
Received 2 February 2017
Received in revised form 10 April 2017
Accepted 6 June 2017

Keywords:
Cross section adjustment
Systematic error
Stochastic error
Fast reactor

ABSTRACT

A new cross section adjustment method has been derived in which systematic errors in measured data and calculated results of neutronics characteristics are estimated and removed in the adjustment. Bias factors which are the ratio between measured data and calculated results are used to estimate systematic errors. The difference of the bias factors from unity is caused generally by systematic errors and stochastic errors. Therefore by determining whether the difference is within the total stochastic errors of measurements and calculations, systematic errors are estimated. Since stochastic errors are determined for individual confidence levels, systematic errors are also dependent to the confidence levels. The method has been applied to cross section adjustments using 589 measured data obtained from fast critical assemblies and fast reactors. The adjustments results are compared with those of the conventional adjustment method. Also the effect of the confidence level to the adjusted cross sections is discussed.

1. Introduction

In designing fast reactors such as inherent safety reactors (Kawashima et al., 1991) and minor actinides transmutation reactors (Fujimura et al., 2011) it is desirable to use best-estimate calculation tools with reliable nuclear data to reduce calculation errors. As for core calculation tools deterministic codes and Monte-Carlo codes have been developed such as NSHEX (Ikeda and Takeda, 1994; Sugino and Takeda, 1996; Sugino and Kugo, 2011), VMONTO (Morimoto et al., 1989; Ishii et al., 1989). Monte-Carlo codes can treat any complicated geometry and can reduce standard errors by using a lot of neutron histries.

Also Monte-Carlo codes can use the continuous energy cross sections, while the deterministic codes use group-wise cross sections.

In designing MA transmutation fast reactors which are important to reduce MAs with long-lived radioactivity and high decay heat contained in high level radioactive wastes,one has to consider the effect of uncertainties in MA cross sections to core performance parameters. The cross sections of MAs such as Np-237 and Am-241 have large uncertainties in higher energy ranges. Therefore the calculated MA's transmutation amount and important core properties such as criticality and sodium void reactivity may have large uncertainties. To reduce the cross section uncertainty effect a cross section adjustment method is very powerful. In conventional cross section adjustments, cross sections are adjusted such that adjusted cross sections reproduce the measured data by considering stochastic errors of measurements (Takeda et al., 1989). In the paper by Salvatores and Palmiotti (2013) the adjustment methods used in ANL, CEA, INF, IPPE, JAEA, JSI, NRG and ORNL are compared, and many interesting results are shown for uncertainties and cross section adjustments for a lot of critical assemblies and reactor cores such as JEZEBEL, ZPPR, FLATTOP, JOYO, ABR (Advanced Burner Reactor of ANL).

The most important issue in applying the adjustment methods is to make sure that large systematic errors are not involved. In the paper by Salvatores and Palmiotti (2013) an adjustment margin has been introduced to check the consistency of the combined experimental, calculation, and nuclear data uncertainties with the observed discrepancies between experimental and calculation results (bias factor).

The present paper corresponds to an extension of the adjustment margin factor to extract systematic errors included in experiments and calculations. Bias factors which correspond to the ratio between measured and calculated results of neutronics parameters are used, and the difference from unity has been investigated by comparing with the standard deviations of the sum of stochastic errors caused from uncertainties of measurements, calculations

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http://dx.doi.org/10.1016/j.anucene.2017.06.011
0306-4549/

and cross sections. Using the sum of the stochastic errors and the confidence level of the occurrence of the stochastic errors we have estimated the systematic errors. The systematic errors estimated have been used to remove that from the experimental and calculation results in cross section adjustments. In the paper by Takeda (Takeda, 2016) we introduced the adjustment method, and applied it to a specific core.

In this paper we discuss the dependence of the estimated systematic errors on the cross section covariance data, and the relation between the systematic errors and the parameter (χ) used in JAEA for discarding experimental data (Salvatores and Palmiotti, 2013). Furthermore the method has been applied to the cross section adjustment by using many experimental data obtained from ZPPR (NEA Nuclear Science Committee, 2010), ZEBRA (NEA Nuclear Science Committee, 2010), BFS (NEA Nuclear Science Committee, 2010), MASURCA (Smith et al., 1997, 1998), SEFOR (Noble et al., 1970, 1972; Hazama and Tommasi, 2004), LANL small cores (NEA Nuclear Science Committee, 2009), JOYO (NEA Nuclear Science Committee, 2010; Osaka et al., 2003; Koyama and Mitsugashira, 2008; Koyama et al., 2010), PFR (Shinohara et al., 2003; Tsujimoto et al., 2003), FCA (Okajima et al., 2008), MONJU (Hazama et al., 2012) and Yayoi (Harada et al., 2009). The effect of the new adjustment to the calculated results after the adjustment, and the adjusted cross section will be discussed. Furthermore the effect of the parameter expressing the confidence level to the results will be discussed. Before presenting numerical results we briefly present the new method in Chap. II, and discuss the importance of the cross section covariance data in estimating systematic errors and the relation between the present method and the parameter χ used in discarding experimental data. Numerical results obtained for the new method are compared with those for the conventional adjustment method in Chap. III. Chap. IV describes some conclusions.

2. Theory

Let us briefly show the new method for removing systematic errors in measurements and calculations in cross section adjustments. The ratio between a calculated and a measured data of a neutronics parameter is denoted as a bias factor, and is defined by

$$f = \frac{R_e}{R_c} \approx 1 + (R_{eb} - R_{cb}) + (R_{es} - R_{cs} - S\Delta\sigma) \quad (1)$$

where Re and Rc are measured and calculated values of a neutronics parameter, and

R_{eb}: Relative systematic error of measured data
R_{cb}: Relative systematic error of calculated data
R_{es}: Relative stochastic error of measured data
R_{cs}: Relative stochastic error of calculated data
S: Sensitivity coefficient of Rc relative to cross sections
$\Delta\sigma$: Cross section error

Next we take an average of the bias factor. The average means taking average of cross sections used, calculations and measurements. The cross sections are distributed around the mean values with the uncertainties given by a covariance data, and the mean neutronics parameters are calculated by the mean cross sections. Calculation results have mean values and standard deviations when the Monte-Carlo method is used because parameters are calculated using many neutron histories. Measurement results are also the averages of several measured data. The average corresponds to this type of averaging. Applying this averaging to the bias factor, the stochastic errors disappear. So the average of f becomes

$$\bar{f} = 1 + (R_{eb} - R_{cb}) \quad (2)$$

Therefore, the variance of f is given by

$$V(f) = E(|f - \bar{f}|^2) = V(R_{es}) + V(R_{cs}) + SWS^T \quad (3)$$

where $V(R_{es})$ and $V(R_{cs})$ are the covariances of the measurements and calculations, and W is the "true" cross section covariance data. The standard deviation σ is defined by the square root of the above equation. In calculating the standard deviation we used only the diagonal values of the covariance (3). However in the cross section adjustment shown below we considered not only the diagonal values but also the off-diagonal values.

One can say that when there is no systematic error the bias factor f should be in the range of

$$1 - c\sigma < f < 1 + c\sigma \quad (4)$$

with the confidence level of 68% (c = 1), 95% (c = 2) and 99% (c = 3). On the contrary, if the bias factor is outsides the range one can say that at least there is systematic errors defined by the following equation with the confidence level of c

$$R_{eb} - R_{cb} = \begin{cases} f - 1 - c\sigma \text{ for } f > 1 + c\sigma \\ f - 1 + c\sigma \text{ for } f < 1 - c\sigma \end{cases} \quad (5)$$

Here it is noted that the estimated systematic error is strongly dependent on the total stochastic error σ as easily seen from Eqs. (4) and (5). Usually the main contributor to σ is the cross section error. In the present situation it is rather difficult to have a reliable cross section covariance data. For-example, there are a large difference between covariance data associated with main nuclear libraries. If one of the cross section library generates C/E close to unity and large uncertainties associated with the data, the systematic errors will be very small for the same set of experimental data. This shows that the numerical results for the present method are very much dependent on the reliability of the cross section covariance data and the problem has to be addressed in the future.

Next let us discuss the relation between the present method of estimating systematic errors and the parameter χused to discard experimental data. Japan Atomic Energy Agency (JAEA) uses the parameter χ calculated by χ=(f-1) /σ in determining whether experimental data are useful or should be discarded. They check the parameter $\chi$for individual experimental data and discard the experimental data when χ is larger than 2. They use the experimental data in the cross section adjustment only when χ is smaller than 2. Thus the JAEA methodology is the "a priori" selection of the experimental data using the parameter χ. In the present method the parameter χ is replaced by the confidence level c, and when the parameter χ is larger than c (=1, 2, 3) systematic errors are estimated from the difference between χ and c (=1, 2, 3). Thus all the experimental data are used in the present method, and the adjusted cross sections are different each other. Let us consider the difference between the two methods. As is shown in Chap. III there are many cases where χexceed 2 (see Table 1 for example) especially for the reaction rate ratios including minor actinides such as Cm-242, Cm-244. The JAEA methodology discards the data, and the improvement of the cross sections of Cm-242 and Cm-244 cannot be expected. In the present method these data are used to adjust the cross sections, and the present method using c larger than 3 gives us information about the improvement of the cross sections of Cm-242 and Cm-244, which correspond to the same result as the conventional cross section adjustment method.

Finally let us derive a new cross section adjustment method using the above method for the systematic errors. The adjusted cross section is determined such that the calculated results by the adjusted cross section approach to the measured data after removing the systematic errors from the calculated and the