EPJ Web of Conferences **281**, 00004 (2023) https://doi.org/10.1051/epjconf/202328100004
CW2022

Development of adjusted nuclear data library for fast reactor application

Kenji Yokoyama[1,*]

[1]Japan Atomic Energy Agency, Fast Reactor Cycle System Research and Development Center, Oarai-machi, Ibaraki 311-1393, Japan

Abstract. In Japan, development of adjusted nuclear data library for fast rector application based on the cross-section adjustment method has been conducted since the early 1990s. The adjusted library is called the unified cross-section set, which is an ABBN-type group constant set with 70-group energy structure. The first version was developed in 1991 and is called ADJ91. After that, ADJ98, ADJ2000, ADJ2000R, and ADJ2010 were constantly developed. For instance, ADJ2010 was developed based on JENDL-4.0, which provides covariance data needed to apply the cross-section adjustment method, by using 488 integral experimental data acquired in typical fast reactor systems. ADJ2010 has been used as the standard cross-section set for nuclear design in the fast reactor cycle technology development project (FaCT) and the succeeding fast reactor projects. In parallel, the integral experimental data were further expanded to improve the design prediction accuracy of the core loaded with MA and/or degraded Pu. Using the additional integral experimental data, development of the next version of ADJ2017 was started in 2017. In 2022, the latest unified cross-section set AJD2017R was developed based on JENDL-4.0 by using 619 integral experimental data. An overview of the latest version with a review of previous ones will be shown.

On the other hand, the latest Japanese evaluated nuclear data library JENDL-5 was released at the end of 2021. In the development of JENDL-5, some of the integral experimental data used in ADJ2017R were explicitly utilized in the nuclear data evaluation. However, this is not reflected in the covariance data. This situation needs to be considered when developing a next version of the unified cross-section set based on JENDL-5. Preliminary adjustment calculation based on JENDL-5 is performed using C/E (calculation/experiment) values simply evaluated by a sensitivity analysis. The preliminary result of the JENDL-5-based adjustment will be also discussed.

1 Introduction

In the development of the neutronics analysis method for fast reactors in Japan, application research of the cross-section adjustment method [1] has been conducted since the early 1990s. In the core design study of an innovative nuclear reactor such as fast breeder reactors, it is important to improve the prediction accuracy of nuclear parameters from the viewpoint of both safety and economics. Several adjusted nuclear data libraries, which are called unified cross-section sets in the sense that the adjusted cross-section set unifies the differential data and the integral data, have been developed based on the cross-section adjustment theory and applied for fast reactor design work [2]. On the other hand, we in JAEA have been collecting and analyzing integral experimental data related to fast reactors for the application of the cross-section adjustment method in order to develop our own integral experimental database. Some of the integral experimental data included in the database are also registered in the International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhEP) [3]. For instance, nine ZPPR experimental cores named ZPPR-9, -10A, -10B, -10C, -13A, -17A, -18A, -18C, and -19B, which are mock-up critical experiments for sodium-cooled MOX-fueled fast reactors in the JUPITER cooperative program between the United States and Japan [4], are registered as benchmarks in the IRPhEP handbook. In addition, the criticality, control rod worth, fuel replacement reactivity, sodium void reactivity, and burnup reactivity coefficient measured in performance tests of the experimental fast reactor JOYO MK-I in Japan are also registered as benchmark problems [5, 6].

The adjusted (unified) library is an ABBN-type group constant set with 70-group energy structure for fast reactors, which is based on the format of UFLIB [7]. The first version was developed in 1991 and is called ADJ91 [8]. After that, ADJ98, ADJ2000, ADJ2000R, and ADJ2010 were developed [9]. In 2022, the latest unified cross-section set AJD2017R [10], which is a revised version of ADJ2017 [11], was developed based on JENDL-4.0 [12] by using 619 integral experimental data. The results of ADJ2017 and ADJ2017R in detail are compiled in technical reports [10, 11]. In the present paper, an overview of the latest version with a review of previous ones will be shown.

On the other hand, the latest Japanese evaluated nuclear data library JENDL-5 [13] was released at the end of 2021. In the development of JENDL-5, some of the integral experimental data, which were also used in the development of ADJ2017R, were explicitly used in the

*e-mail: yokoyama.kenji09@jaea.go.jp

nuclear data evaluation. However, this is not reflected in the covariance data. These changes in circumstances need to be taken into account in the development of a next version of the unified cross-section set by using JENDL-5 as a base library. Preliminary adjustment calculation based on JENDL-5 is performed using C/E (calculation/experiment) values simply evaluated by a sensitivity analysis. The preliminary result of the JENDL-5-based adjustment will be also discussed.

2 Overview of unified cross-section set

2.1 Brief development history of unified cross-section set

Table 1 shows the unified cross-section sets developed in Japan. As mentioned before, the first version is ADJ91, which was developed in 1991 [8]. The base nuclear data library of ADJ91 is JENDL-2 [14]. The next version ADJ98 [15] was developed in 1998. The base library of ADJ98 was changed to JENDL-3.2 [16], which was the latest Japanese nuclear data library at that time. ADJ98 was used as a standard cross-section set for nuclear design in the project of the feasibility study on commercialized fast reactor cycle systems (FS) started from 1999 in Japan. This version still utilized only the integral experimental data of ZPPR. The further next version ADJ2000 [17] was developed in 2000, and its revised version, ADJ2000R [18], was developed in 2002. In ADJ2000, integral experimental data measured in cores other than ZPPR were used for the first time. In the development of ADJ2000, the integral experimental data measured in FCA, JOYO, and BFS are mainly added. This extension of the integral experimental data was an important milestone. The integral experimental data obtained in a single experimental facility might be biased, and it is difficult to remove the bias by the cross-section adjustment method. For this reason, it was necessary to introduce the other integral experimental data measured in independent facilities; extensive efforts were made to expand the database. ADJ2000 and ADJ2000R were also used as a standard cross-section set in FS.

Following the release of JENDL-4.0 [12] in 2011, ADJ2010 [9, 19, 20] was developed by extending the database and reanalyzing the integral experimental data with JENDL-4.0. ADJ2010 has been used as the standard cross-section set for nuclear design in the fast reactor cycle technology development project (FaCT) and the succeeding fast reactor projects. In the development of ADJ2010, a significant improvement was made to the method of evaluating uncertainty and correlation coefficient, i.e., covariance data, of the integral experiments. As a methodology for quantifying the correlation coefficient between the integral experimental data, the "error factor correlation method" was proposed [19]. This methodology is described in the OECD/NEA report [21] as a recommended method for evaluating the correlation coefficient between the integral experimental data when applying the cross-section adjustment method.

The latest adjustment cross-section set at the moment is ADJ2017R [10], which is a minor revision of ADJ2017 [11] developed in 2017. In the development of ADJ2017, integral experimental data regarding minor actinoides (MAs) and degraded plutonium (Pu) were added to improve the design accuracy of the core loaded with MA and/or degraded Pu.

2.2 Recent versions of unified cross-section set, ADJ2017 and ADJ2017R

2.2.1 Overview of ADJ2017

ADJ2017 uses JENDL-4.0 as a base library as well as the previous version ADJ2010 and is an adjusted cross-section set that intentionally introduces as many integral experimental data related to MAs and degraded Pu as possible.

In the development of the previous version ADJ2010, a total of 643 integral experimental data were analyzed, and 488 of the integral experimental data were finally selected to be used for the cross-section adjustment. In contrast, a total of 719 integral experimental data were analyzed, and 620 integral experimental data were eventually adopted to develop ADJ2017. As mentioned before, the increased integral experimental data are mainly related to MA and degraded Pu.

For the main neutronic characteristics of conventional sodium-cooled MOX-fuel fast reactors, ADJ2017 shows almost the same performance as ADJ2010. In addition, for neutronic characteristics related to MA and degraded Pu, ADJ2017 improves the C/E values of the integral experimental data sets, and reduces the uncertainty induced by the nuclear data.

2.2.2 Overview of ADJ2017R

ADJ2017R is a minor revision and is basically the same as ADJ2017, but the following two points were revised.

The first point is to unify evaluation methods of the correlation coefficients of experimental uncertainty. In a process of continuous review, it was found that different methods were used for evaluating a common uncertainty of the experimental correlation coefficient. The experimental correlation coefficients were, therefore, reevaluated for all the integral experimental data in the development of ADJ2017R.

The second point is to review the integral experimental data used for the cross-section adjustment. One of the experimental values of composition ratio after irradiation of Am-243 sample was eliminated from the cross-section adjustment because it has a very small uncertainty compared to the others, and the reason could not be clearly explained. In the development of ADJ2017R, a total of 619 integral experimental data, one less than ADJ2017, were used.

Table 2 shows an overview of the integral experimental data used for the development of ADJ2017R. The above two revisions have little effect on the cross-section adjustment results, but they are important from a quality assurance point of view.

Table 1. Features of unified (adjusted) cross-section sets developed in Japan.

	ADJ91/98 (1991/1998)	ADJ2000/2000R (2000/2001)	ADJ2010 (2010)	ADJ2017/2017R (2017/2020)
Base library	JENDL-2/3.2 (1989/1994)	JENDL-3.2 (1994)	JENDL-4.0 (2010)	JENDL-4.0 (2010)
Covariance of nuclear data	rough estimation	JENDL-3.2[1]	JENDL-4.0	JENDL-4.0
Number of energy group	18 (70)[2]	18 (70)[2]	70	70
Number of adjusted parameters	σ_∞: 32/37 χ: 2 β: 6	σ_∞: 41 χ: 2 β: 6 SSF: 1	σ_∞: 155 χ: 2 β: 11 SSF: 1 PFP: 4	σ_∞: 179 χ: 19 β: 20 SSF: 1 PFP: 4
Number of integral experiments	82/185 (ZPPR only)	237 (+ FCA, JOYO, BFS, MASURCA, and LANL)	488 (+ ZEBRA, SEFOR, MONJU(1994), JOYO(MA sample), and BFS(Np))	620/619 (+ ZPPR(D-Pu worth, F41/F25), BFS(D-Pu worth), MONJU(2010), ZEBRA(D-Pu fission RRR), FCA(MA fission RRR), JOYO(MA sample (Pu-241/Pu-240)), PFR(MA sample), and YAYOI(Np capture RRR))

[1]: The covariance data were evaluated after the release of JENDL-3.2.
[2]: The cross sections were adjusted with 18 groups and expanded to 70 groups.
σ_∞: infinite dilute cross section, χ: fission spectrum, β: delayed neutron fraction, RRR: reaction rate ratio, SSF: self-shielding factor, PFP: pseudo fission product, D-Pu: degraded plutonium

3 Issues on development of next version

3.1 Background

As can be seen from the above explanation, the recent development of the unified cross-section set has been based on JENDL-4.0 for over a decade since JENDL has not had a major revised version since JENDL-4.0 was released in 2010. However, a new major version of JENDL-5 was finally released at the end of 2021. We will proceed with the development of the unified cross-section set based on JENDL-5.

On the other hand, the research situation on the cross-section adjustment methodology has greatly changed in the last decade. In particular, a series of activities started from 2005 in the framework of Sub-Groups (SGs) under the Working Party on International Nuclear Data Evaluation Cooperation (WPEC) in OECD/NEA. One of the important conclusions by the WPEC/SG26 [22] was that a combined use of integral experiments and differential nuclear data measurements is necessary to meet the design target accuracies because many of reactor core target accuracies are not likely to be achieved only with the current differential data. Following this suggestion, a new sub-group SG33 [21] was started in 2009. In SG33, a world-wide comparative study of theoretical formulas of the cross-section adjustment methodology and practical benchmark exercises were conducted. These activities started mainly from the viewpoint of improving the target accuracy of nuclear reactors. After that, activities were handed over to SG39 and SG46 [23, 24], and methodology for effectively utilizing the cross-section adjustment method for nuclear data evaluation and validation were also examined.

In addition, through these activities, an important issue regarding the covariance data of the nuclear data library has become widely known. In the validation of the nuclear data library, benchmark tests using integral experimental data are commonly performed. However, if the information obtained from the benchmark tests using integral experimental data is reflected only in the mean value of the nuclear data, an inconsistency between the mean value and the covariance data will occur. This is because the correlation coefficients in the covariance data should be changed because the integral experimental data are often sensitive to the other nuclear data.

3.2 Proposal from IAEA consultants meeting: general-purpose library and application library

There have been various discussions on this issue, but nevertheless, the discussions and proposals at the IAEA consultants meeting [25], which was held in 2017 soon after the issue became a hot topic, are still informative. In the summary report of the IAEA consultants meeting, the nuclear data libraries are categorized into two groups: A) general-purpose libraries and B) application libraries. The application library is a nuclear data library derived from the general-purpose library for the purpose of using it within a limited range. For simplicity, in the present paper, the general-purpose library and application library are called “A-file” and “B-file”, respectively.

The summary report suggests creating covariance data of B-file if the use of integral experimental data in the

Table 2. Integral experimental data used for ADJ2017R.

Facility	Core name	Features	Parameters
ZPPR	9, 10A – 10C	600-800 MWe-class, two-region homogeneous MOX cores.	k_{eff}, RR, CRW, SVR, DR(sample)
	13A	650 MWe-class, Radially-heterogeneous MOX cores.	k_{eff}, RR, CRW, SVR, DR(sample)
	18A, 18C, 19B	1000 MWe-class, two-region homogeneous MOX cores with enriched-uranium regions.	k_{eff}, RR, CRW, SVR
ZEBRA	MZA	550 liter-sized one-region MOX core as a clean benchmark.	k_{eff}, SVR
	MZB, MZC	2,300 liter-sized two-region homogeneous MOX cores to simulate the prototype fast reactor MONJU.	k_{eff}, CWR, SVR
JOYO	MK-I	300 liter-sized 50/75MWt fast power reactor core with MOX and enriched-uranium fuel with blanket	k_{eff}, CWR, SVR, ZMRR, ITC, BRC
	MK-II	240 liter-sized 100MWt fast power reactor core with MOX and enriched-uranium fuel with blanket	MA post-irradiation test
MONJU	Start-up Tests	280MWe prototype fast breeder reactor with two-region homogeneous MOX core	k_{eff}, CRW, ITC
BFS	62-1 – 62-5, 66-1	3,400 liter-sized three or four-region enriched-uranium and/or MOX fuel cores with or without radial blankets.	k_{eff}, RR, CRW, SVR
	67, 69, 66	10kg of NpO_2 loading cores in central MOX region with various grade Pu.	k_{eff}, RR, CRW, SVR
MASURCA	ZONA-2B	380 liter-sized core in the CIRANO experiment series, which aimed at the study of Pu burner cores.	SVR, ZMRR
SEFOR	CORE-I, II	20MWt power fast power reactor core fueled with MOX and cooled with sodium	DR(whole core)
LANL	FLATTOP-Pu, -25, GODIVA, JEZEBEL, JEZEBEL-Pu240	sphere-shaped cores of approx. ten cm in diameter with metallic fuel consisted of ^{239}Pu, degraded Pu or ^{235}U.	k_{eff}
FCA	FCA IX-1 – 7	systematically changed neutron spectra cores with uranium and diluent (graphite and stainless steel).	TRU fission rate ratio
YAYOI	–	fast neutron source reactor with two irradiation holes called Glory and Grazing.	

k_{eff}: criticality, RR: reaction rate, CRW: control rod worth, SVR: sodium void reactivity, DR: Doppler reactivity, ZMRR: zone material replacement reactivity, ITC: isothermal temperature coefficient, BRC: burnup reactivity coefficient

nuclear data evaluation is not reflected in the covariance data. Since the application libraries are often in multi-group data, it is possible to create full-matrix covariance data.

According to the definition of the summary report, the B-file has the following four classifications [25]:

1) Mean values and covariances are preserved[1], only additional correlations (+/-) are added[2].

2) Mean values and standard deviations are preserved, correlations are added/updated.

3) Mean values are preserved, standard deviations and correlations are added/updated.

4) Both mean values and covariances are updated.

3.3 Discussions in working group of JENDL committee

In 2018, the following year, the JENDL Committee established a new working group aimed at promoting the use of covariance data. This working group had been active for three years and published a report [26]. There were various discussions on the use and development of covariance data in the working group; the foregoing issue was also discussed with reference to the proposals of the IAEA consultants meeting. Although there was a discussion that we should not use any integral experimental data in the nuclear data evaluation, the working group concluded that it would be impractical to abandon high-performance libraries based on the integral benchmarks. According to the conclusions, discussions were held to explore realistic countermeasures. An important suggestion derived from the discussions is that nuclear data evaluators should inform users of the use of integral experimental data in the nuclear data evaluation.

There was also a discussion about how users should handle the covariance data in their own problems when they have access to a list of integral experimental data used in the nuclear data evaluation. In this discussion, the preparation of B-file proposed by the IAEA consultants meeting was exercised. In the working group, the B-file classification of 3) proposed by the IAEA consultants meeting was adopted, and a 70-group covariance data set as a B-file was created using the JENDL-4.0-based cross-section set for fast reactors. In the exercise, the B-

[1] In other words, A-file is used as is.

[2] As an example of this case, the summary report [25] presents a study in which the same correlation factors are added to all energy groups.

file of covariance data was created with the mathematical formula of the cross-section adjustment method by tentatively using eight criticality data used in the development of JENDL/AC-2008 [27]. As a result, it was confirmed that the uncertainty evaluated from the variation of C/E values and the uncertainty evaluated from the B-file of covariance data for criticality, reaction rate, and reactivity are comparable.

The conclusions on this issue in the working group are summarized:

- It is necessary to use integral experimental data in the nuclear data evaluation in order to improve the prediction accuracy of integral parameters.
- At this moment, it is difficult to reflect the use of integral data in the covariance data of the evaluated nuclear data files.
- It is recommended for nuclear data users to reflect the use of integral data to their applications, for instance, by using a data assimilation method.
- Nuclear data evaluators should clearly explain and inform users when integral data are used in the nuclear data evaluation

3.4 Issues on development of unified cross-section set based on JENDL-5

In the working group exercise, we could not use JENDL-5 since it had not yet been released, but now we can use JENDL-5. In the first release of JENDL-5, the use of integral data in the nuclear data evaluation is not reflected in the covariance data. However, according to the suggestion of the working group, the use of the integral data used have been clarified [13]. In the nuclear data evaluation of JENDL-5, many integral experimental data of fast reactors, which were used to create ADJ2017R, were also utilized.

These circumstances raise two main issues to be considered. The first issue is the handling of covariance data. In the development of the unified cross-section set, the covariance data of the base nuclear data library, i.e., the prior covariance data, is required as input data for the cross-section adjustment calculation. In a precise sense, therefore, covariance data that is consistent with the mean values of JENDL-5 is necessary when creating an unified cross-section set using JENDL-5 as a base library. As mentioned before, JENDL-5 uses the integral experimental data to adjust the mean values of the nuclear data, but this is not reflected in the covariance data. For this reason, covariance data consistent with the mean value of JENDL-5 were prepared first for the cross-section adjustment calculation. In response to the circumstances, a B-file of JENDL-5 covariance data is created and the cross-section adjustment calculation using the B-file as the prior covariance data is examined.

The second issue is the handling of the integral experimental data that were used in the evaluation of JENDL-5. Generally speaking, it is considered better not to repeatedly use the integral experimental data in the adjustment calculation. Even if the experimental data were actually measured twice, there should be a strong correlation between the two experimental data. Ignoring such a strong correlation in the adjustment calculation would change the result, but the correlation of experimental data used in separate adjustment calculations cannot be considered. For this reason, it is better to avoid the repeated use of the experimental data used in the evaluation of JENDL-5 in our adjustment calculation for creating a unified cross-section set.

4 Preliminary adjustment calculations based on JENDL-5

4.1 Covariance B-file of JENDL-5

In the evaluation of JENDL-5, an adjustment calculation was applied by using the generalized least squares method (GLS), in which fission, capture, and elastic scattering of U-235, U-238, and Pu-239 were adjusted [13]. In addition to the GLS-based adjustment calculation, there are several descriptions on the use of integral experimental data.

We checked the descriptions on the use of integral experimental data in the evaluation of JENDL-5, and listed up the integral experimental data that were commonly used in the development of ADJ2017R. As a result, it was confirmed that there are 82 nuclear characteristics including criticality, reaction rate ratio, sodium void reactivity, and composition ratios of irradiated MA samples. In order to create a consistent B-file of covariance data, it is desirable to confirm the details of how to use these integral experimental data and reflect the use in the B-file. In the present study, however, we adopt a simple method of creating the B-file by using the posterior covariance formula of the cross-section adjustment method, which is the same method adopted in the exercise of the JENDL Committee's working group.

Thus, a B-file of 70-group covariance data were created; this B-file is used as the prior covariance for the preliminary cross-section adjustment based on JENDL-5 in the present paper. Although this method of creating a B-file of covariance data is simplified, it is considered that one of realistic methods for creating a JENDL-5-based adjusted cross-section set at the moment.

4.2 Calculation cases

Three calculation cases are considered for the purpose of comparative study. Table 3 shows a summary of the calculation cases compared to ADJ2017R.

In the first case, the original covariance data of JENDL-5 is used as the prior covariance data, and the cross-section adjustment calculation is performed using the same total set of the integral experimental data as used in the development of ADJ2017R. Note that the integral experimental data are used repeatedly in this case because JENDL-5 utilizes the 82 integral experimental data that were also used in the development of ADJ2017R. Although no explicit adjustment using integral experimental data was made in the major releases prior to JENDL-5,

Table 3. Calculation cases

	ADJ2017R	ADJJ5case1	ADJJ5case2	ADJJ5case3
Base library	JENDL-4.0	JENDL-5		
Number of integral data	619		537 (= 619 - 82[1])	
Covariance data	JENDL-4.0	JENDL-5		JENDL-5 B-file
Evaluation of C/E values	Deterministic or Monte Carlo	Sensitivity analysis		
Repeated use of integral data	—	Yes	No	No
Inconsistency of covariance data	—	Yes	Yes	No[2]

[1]: The common 82 integral experimental data were used in JENDL-5 and ADJ2017R.
[2]: The inconsisency between mean values and covarinace data was eliminated by B-file.

e.g., in JENDL-4.0, the information of the integral experimental data might be implicitly used regardless of the evaluator's intention since the nuclear data evaluators know the results of the integral benchmarks. It is considered that, therefore, the unified cross-section sets developed in the past, including ADJ2017R, are actually in the similar condition as this calculation case. This calculation case is called ADJJ5case1.

In the second case, the original covariance data of JENDL-5 is used, but the integral experimental data utilized in the evaluation of JENDL-5 are eliminated in the cross-section adjustment calculation so as to avoid the repeated use of the same integral experimental data. Note that, in this case, the cross-section adjustment calculation is performed using the covariance data that do not have any information of the use of integral experimental data. In other words, there is a possibility that the mean values may be adjusted inconsistently or overly at the stage of adjustment calculation because it is not possible to take into account the fact that the mean values have already been adjusted in the nuclear data evaluation. In practice, this calculation case should be avoided, but the importance of covariance data in the cross-section adjustment calculation can be checked by comparing with this case. This calculation case is called ADJJ5case2.

The third case is the reference case. In the third case, the B-file of covariance data is used as the prior covariance data, and the cross-section adjustment calculation is performed excluding the 82 nuclear characteristics used in the JENDL-5 evaluation. Although the method of creating the B-file of covariance data is simplified, not perfect, in this case, but at least the use of the 82 integral experimental data in the JENDL-5 evaluation is consistently taken into account and the repeated use of integral experimental data is avoided. This calculation case is called ADJJ5case3.

4.3 The other calculation conditions

In the development of ADJ2017R, the C/E values of JENDL-4.0 were evaluated by a deterministic method or a Monte Carlo method, but these evaluations are very time consuming. In the present study, the C/E values of JENDL-5 were obtained by using sensitivity analysis, in which 70-group sensitivity coefficients and differences of nuclear data between JENDL-5 and JENDL-4.0 were used. This sensitivity analysis is considered to have sufficient accuracy for this study. The other calculation conditions are basically the same as ADJ2017R.

4.4 Calculation results

Figure 1 shows C/E values of criticality. From this figure, it can be seen that ADJ2017R, ADJJ5case1, and ADJJ5case3 have similar results. In general, the same tendencies were seen for the other nuclear characteristics. On the other hand, it can be seen that ADJJ5case2 tends to be quite different. For instance, the C/E values of ZPPR and BFS have not improved much. In particular, the C/E value of GODIVA is getting worse. In ADJJ5case2, the use of the integral experimental data in the evaluation of JENDL-5 is not reflected in the prior covariance. For this reason, the restriction by the covariance data does not work correctly in the adjustment calculation, and incorrect large adjustment is made to improve the C/E values of the other integral experimental data. This result is considered to be a non-physical adjustment result. It also suggests the important role of the prior covariance data when applying the cross-section adjustment method.

Figure 2 shows C/E values of reaction rate ratio of C28/F49 (U-238 capture to Pu-239 fission). From this figure, it can be seen that all calculation cases give almost the same results for this nuclear characteristic. The differences of the calculation cases had little effect because the C28/F49 reaction rate ratios were not used in the evaluation of JENDL-5.

Figure 3 shows C/E values of reaction rate ratios of F42/F49 (Pu-242 fission to Pu-239 fission) and F64/F49 (Cm-244 fission to Pu-239 fission). These are the integral experimental data related to the degraded Pu and MA, which were introduced in the development of ADJ2017/ADJ2017R. In JENDL-4.0, F42/F49 was slightly overestimated, and F64/F49 was clearly overestimated. From this figure, it can be seen that ADJ2017R improves these overestimations. It can be seen that the C/E values of JENDL-5 are significantly improved; these benchmark results were also used in the evaluation of JENDL-5. In ADJJ5case3, where the integral experimental data utilized in the evaluation of JENDL-5 are not repeatedly used in the adjustment calculation, it is seen that the results of F64/F49 in ADJJ5case3 are almost the same as JENDL-5. In addition, the results of F64/F49 in ADJJ5case3 were not improved as much as ADJ2017R. If they had not been used in the evaluation of JENDL-5, they might have been improved to the same level as ADJ2017 by the cross-section adjustment. The results of ADJJ5case3 will be acceptable in practice, but these results suggest that there should be cases where it is better

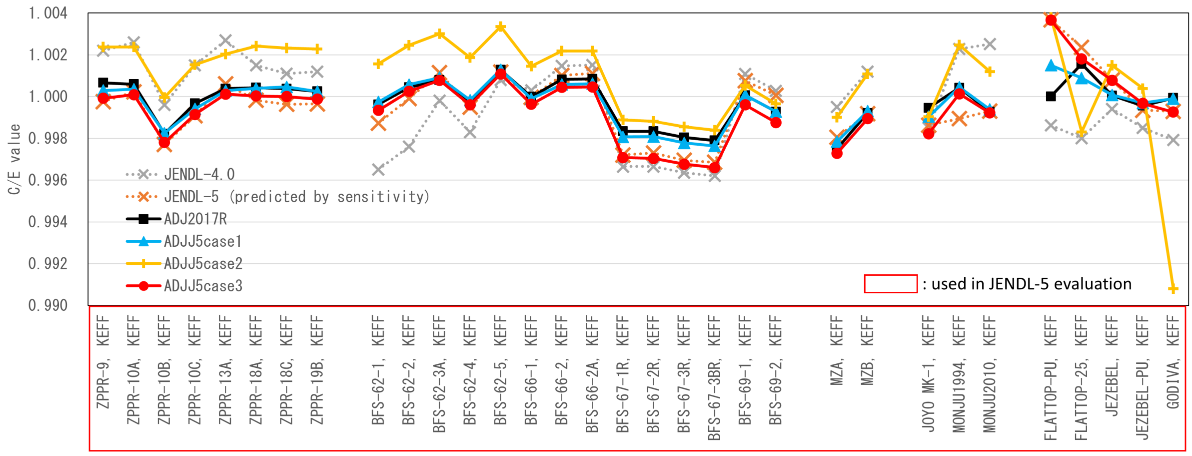

Figure 1. C/E values of criticality

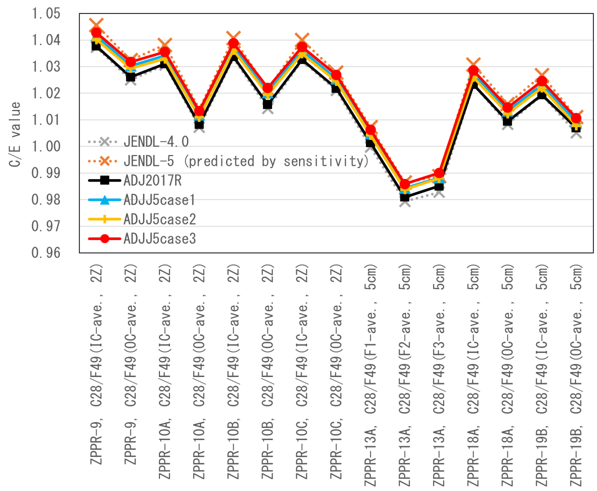

Figure 2. C/E values of reaction rate ratio of C28/F49

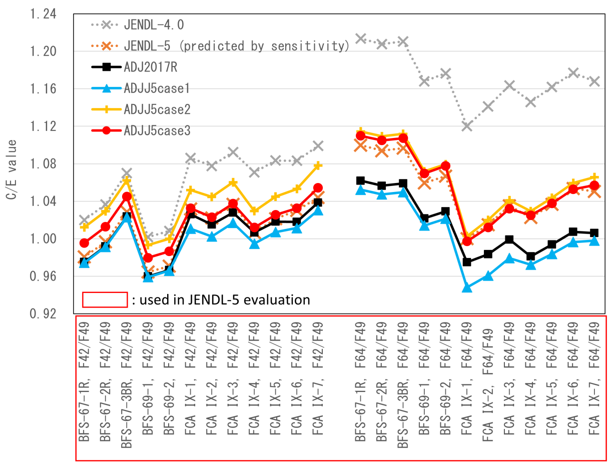

Figure 3. C/E values of reaction rate ratio of F42/F49 and F64/F49

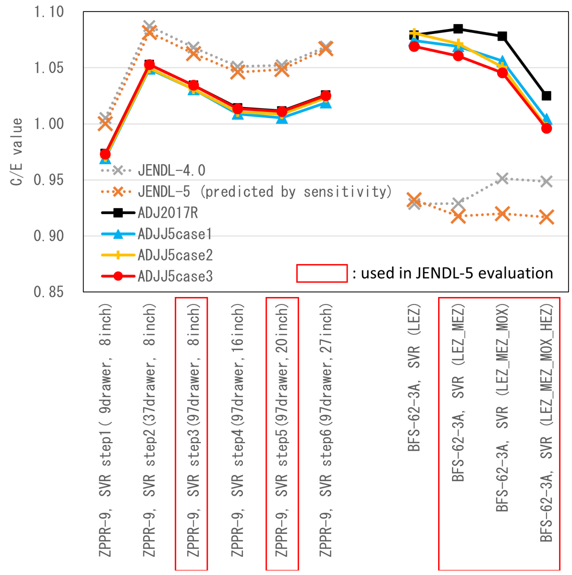

Figure 4. C/E values of sodium void reactivity

for the users to make adjustments directly. On the other hand, in ADJJ5case1, it is seen that the C/E values of F64/F49 are smaller than those of ADJ2017R. Since the same integral experimental data were used twice in this case, it is considered that the C/E values are over-adjusted.

Figure 4 shows the C/E values of sodium void reactivity. In the evaluation of JENDL-5, the sodium void reactivities of ZPPR-9 step3 and step5, BFS-62-3A LEZ_MEZ, LEZ_MEZ_MOX, and LEZ_MEZ_MOX_HEZ, were utilized. From this figure, it can be seen that the results of ADJJ5case1, ADJJ5case2 and ADJJ5case3 are almost the same. This is probably because the benchmark results of sodium void reactivity, which have relatively large uncertainty, do not have a strong impact on the evaluation of JENDL-5 compared to those of criticality and reaction rate ratio.

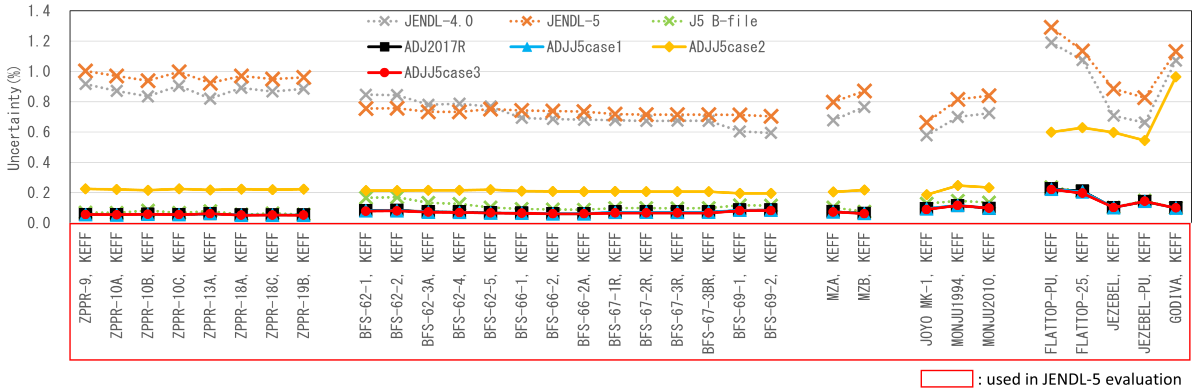

Figure 5. Nuclear-data-induced uncertainty of criticality

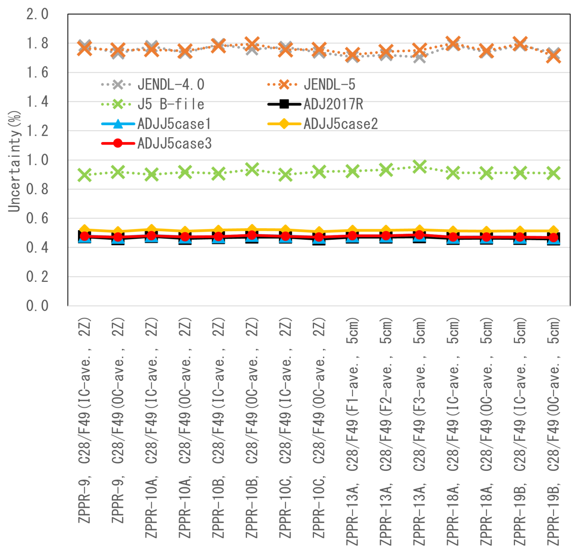

Figure 6. Nuclear-data-induced uncertainty of reaction rate ratio of C28/F49

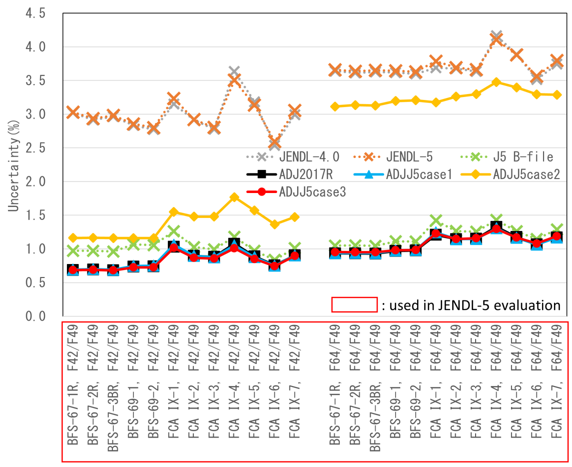

Figure 7. Nuclear-data-induced uncertainty of reaction rate ratio of F42/F49 and F64/F49

4.5 Nuclear-data-induced uncertainty

Figure 5 shows the uncertainty due to nuclear data for criticality. From this figure, it is seen that the nuclear-data-induced uncertainties evaluated with the B-file are considerably small. In the evaluation of JENDL-5, the all criticalities shown here are used, and the uncertainties evaluated with the B-file are almost the same as in AJD2017R. Although the adjustment calculation performed in the evaluation of JENDL-5 is not exactly the same as that in the creation of B-file, the true JENDL-5 covariance data are expected to give considerably smaller uncertainties with respect to criticality.

Figure 6 shows the uncertainties due to nuclear data of reaction rate ratio C28/F49. In the evaluation of JENDL-5, the integral experimental data of C28/F49 were not used, but since it is the ratio of the major reactions in fast reactors, it is considered that the information of C28/F49 is are included in the other integral experimental data such as criticality. The uncertainties of the B-file are approximately 0.9%, which are considerably smaller than 1.8% of JENDL-5. From this result, it is expected that the true JENDL-5 covariance data has correlations that reduce the uncertainty due to nuclear data of C28/F49.

Figure 7 shows the uncertainties due to nuclear data with respect to F42/F49 and F46/F49. The uncertainties of the B-file are small, and is almost the same as the uncertainties of ADJ2017R. As with the other integral experimental data, the true JENDL-5 covariance data would reduce the uncertainties of F42/F49 and F64/F49.

Figure 8 shows the uncertainties due to nuclear data of sodium void reactivity. Although the uncertainties of the B-file are smaller than those of the original JENDL-5, they are not as small as those of ADJ2017R and ADJJ5cases. From this result, it is considered that the number of integral experimental data used in the JENDL-5 evaluation was not sufficient for the sodium void reactivity compared to that used in the adjustment calculations of ADJ2017R and ADJJ5cases. This may be one of the reasons why the C/E values of the sodium void reactivity did not change significantly depending on the calculation cases.

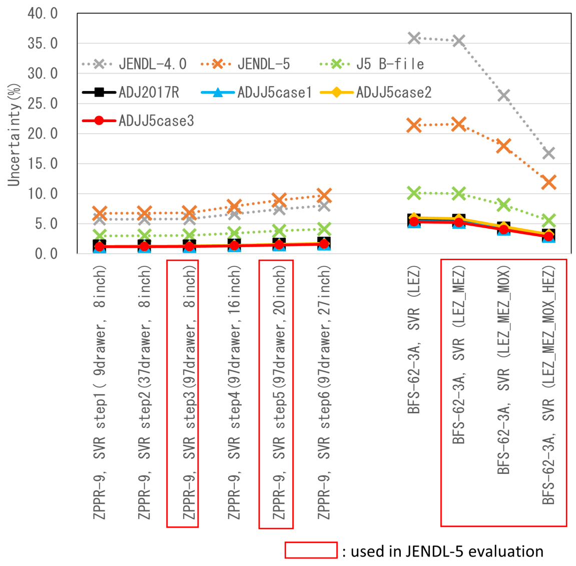

Figure 8. Nuclear-data-induced uncertainty of sodium void reactivity

5 Conclusions

This paper briefly reviews the history of the development of adjusted nuclear data libraries for fast reactors, which are called the unified cross-section sets, and provides an overview of the latest version ADJ2017R. The latest version uses JENDL-4.0 as a base library, but the next version will be developed by using JENDL-5 as the base library because JENDL-5 was released in December 2021. In the evaluation of JENDL-5, integral experimental data were intentionally used for the purpose of improving the accuracy of reactor analysis; an adjustment with the generalized least square method, which is equivalent to the cross-section adjustment method, was also adopted. The use of integral experimental data in the evaluation of JENDL-5, however, has not been reflected yet in the covariance data at the moment. Fortunately, according to the proposal based on the discussions in the working group of the JENDL Committee, the use of integral experimental data in the evaluation were clearly described. Under the present circumstances, we investigated a method of creating an adjusted cross-section set using JENDL-5 as a base library.

In the present paper, since the list of the integral experimental data used in the evaluation of JENDL-5 is available, we used the list to create 70-group covariance data that are more consistent with the mean values of JENDL-5, i.e., an application library (B-file) proposed by the IAEA consultants meeting. Furthermore, we performed preliminary cross-section adjustment calculations using the B-file as the prior covariance. By this procedure, we could create a unified cross-section set based on JENDL-5 that has almost the same performance as the latest version of the unified cross-section set ADJ2017R, which is based on JENDL-4.0. To avoid the repeated use of the integral experimental data used in the evaluation of JENDL-5, we did not use them in the reference case of the preliminary cross-section adjustment calculation. In this case, we found that the adjustment results could be a little worse than ADJ2017R. However, we would like to emphasize that the working group's proposal has shown a realistic, though not perfect, solution at the moment. The use of integral experimental data in the nuclear data evaluation is no longer inevitable because discarding the existing high-performance libraries is impractical. If so, we have no choice but to find a better and more practical solution for the use of integral experimental data in the nuclear data evaluation.

This paper includes a part of the results of "Technical development program on a common base for fast reactors" entrusted to the Japan Atomic Energy Agency (JAEA) by the Ministry of Economy, Trade and Industry (METI). The authors also wish to express their gratitude to Mr. K. Numata of NESI corporation for his valuable comments on the adjustment calculations.

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