ADJUSTMENT OF TOTAL DELAYED NEUTRON YIELDS OF ^{235}U , ^{238}U AND ^{239}Pu BY USING RESULTS OF IN-PILE MEASUREMENTS OF EFFECTIVE DELAYED NEUTRON FRACTION

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ABSTRACT

The cross section adjustment method was applied to total delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu of the JENDL-3.2 file by using experimental results of effective delayed neutron fraction β_{eff} at six cores built in two fast critical facilities of the MASURCA and FCA and a thermal critical facility of the TCA to improve these yields. The adjustment was carried out on the yields given at several incident neutron energy points in the file. Furthermore, to validate these adjusted delayed neutron yields, analyses were performed for the β_{eff} experiments at ZPR fast critical facility. These adjusted yields brought a reduction of uncertainty of calculated β_{eff} and an improvement in agreement of β_{eff} between experiment and calculation.

1. INTRODUCTION

The effective delayed neutron fraction β_{eff} is a key safety parameter of nuclear reactor as the scale of reactivity worths. Total delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu are the most important nuclear data for the calculation of β_{eff}. There are, however, discrepancies of the yields between major evaluated nuclear data files. It is therefore useful to recommend the yields with more reliability by using results of integral experiments.

Benchmark experiments of β_{eff} have been performed so far at two cores fueled with uranium and three cores fueled with plutonium in two fast critical facilities, the MASURCA of Commissariat a l'Energie Atomique(CEA) and the FCA of Japan Atomic Energy Research Institute(JAERI), to estimate the prediction accuracy of β_{eff} of fast reactor[1,2]. The cross section adjustment method[3-7] was applied in the present work to improve the delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu by using the results of these experiments. Furthermore, the result of another β_{eff} experiment performed at a core fueled with uranium in the TCA thermal critical facility of JAERI[8,9] was also used to extend the integral data base for the adjustment. Several experimental techniques were applied to measure the β_{eff} and an intercomparison was made for the β_{eff} values between the different techniques in these benchmark experiments. As a result, experimental values of β_{eff} have been obtained with high reliability in these experiments[1,2,8,9].

The adjustment was made for the JENDL-3.2 delayed neutron yields for which covariances have been evaluated[10]. The adjustment was carried out on the yields given at several energy points in the JENDL-3.2 file. The energy dependence of yield between these energy points, which has been given by a linear interpolation in the file, was taken into account in a sensitivity analysis for the adjustment.

For the validation of these adjusted delayed neutron yields, analyses were performed for the β_{eff} experiments by Bennett and Schaefer at ZPR fast critical facility[11] of Argonne National Laboratory.

2. ADJUSTMENT OF DELAYED NEUTRON YIELDS USING BENCHMARK EXPERIMENTS ON β_{eff}

2.1 BRIEF DESCRIPTION OF BENCHMARK EXPERIMENTS ON β_{eff}

The adjustment of delayed neutron yields was carried out by using results of the β_{eff} experiments at two fast reactor cores in the MASURCA : R2 and Zona2[1], three fast reactor cores in the FCA : XIX-1, XIX-2 and XIX-3[2], and a thermal reactor core of the TCA 1.83U[8,9]. Table I summarizes major characteristics of these cores. All of these cores were simple in geometry. A core-region was surrounded by blanket-regions in the MASURCA and FCA cores. The TCA core-region was surrounded by a reflector-region of water. Figure 1 shows a systematic variation of nuclide contribution to the β_{eff} in these cores. It can be seen in this figure that the principal nuclides of ^{235}U, ^{238}U and ^{239}Pu have dominant contribution to the β_{eff}. Several experimental techniques were applied to measure the β_{eff} and an intercomparison was made for the β_{eff} values between the different techniques in each core. As a result, experimental values of β_{eff} have been obtained with accuracy of better than ±3%.

The analyses for the MASURCA and FCA cores have been carried out by using a 70-energy-group constants set for a fast reactor analysis, JFS-3-J3.2[12], which was produced from the JENDL-3.2 nuclear data file[13]. The analysis for the TCA core has used 107-energy-group constants based on the JENDL-3.2 file, which were prepared for the SRAC thermal reactor analysis code system[14].

The β_{eff} has been calculated with the perturbation theory by

$$\beta_{eff} = \frac{\sum_{m}\sum_{i=1}^{6}\int_{reactor}(\sum_{g'}\chi_{d,i,m,g'}\phi^{\dagger}_{g'})(\sum_{g}\nu_{d,i,m,g}N_m\sigma_{f,m,g}\phi_g)\,dv}{\sum_{m}\int_{reactor}(\sum_{g'}\chi_{g'}\phi^{\dagger}_{g'})(\sum_{g}\nu_{m,g}N_m\sigma_{f,m,g}\phi_g)\,dv}, \qquad (1)$$

where

ϕ_g : Space-dependent forward flux of energy group g,
$\phi^{\dagger}_g$: Space-dependent adjoint flux of group g,
N_m : Region-dependent atomic number density of fissionable nuclide m,

$\nu_{d,i,m,g}$: Delayed neutron yield of group g, family i and nuclide m,

$\chi_{d,i,m,g}$: Delayed neutron spectrum of group g, family i and nuclide m,

$\nu_{m,g}$: Region-dependent number of total neutrons of group g emitted per fission of nuclide m,

χ_g : Region-dependent fission spectrum of group g of fuel,

$\sigma_{f,m,g}$: Region-dependent microscopic fission cross section of group g and nuclide m.

Delayed neutron yields of JENDL-3.2 were used for the calculation where contributions from six nuclides of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{241}Am to the β_{eff} were considered. In the JENDL-3.2, the yields have been given at several incident neutron energy points for these nuclides. It is specified that the yields between these points are obtained by the linear interpolation. Figure 2 shows the energy dependent yields for the principal nuclides of ^{235}U, ^{238}U and ^{239}Pu. This energy dependence is similar to that recommended by Tuttle[15]. Two delayed neutron yield sets prepared in 70-energy-group and 107-energy-group structures were used for the calculation. The former one was produced by using the fission rate as a weighting function. The latter one has been prepared in the SRAC code system. For ^{235}U and ^{239}Pu, the yield of energy group below 1MeV is closer to the yield at the thermal energy point than to those at the other energy points in the file. The delayed neutron spectra evaluated in the ENDF/B-VI[16] have been used in the analyses.

Detailed descriptions on these cores, measurements and analyses of β_{eff} can be found in Refs.[1,2,8,9,19]. The calculated to experiment ratios(C/E) of β_{eff} are also shown in Table I. Discrepancies between experimental and calculated values of β_{eff} were more than the experimental error at two cores of FCA XIX-3 and TCA 1.83U.

Table I. Major characteristics of benchmark cores for β_{eff} experiments and C/E values of β_{eff}

	MASURCA cores		FCA cores			TCA core
Item	R2	Zona2	XIX-1	XIX-2	XIX-3	1.83U
Fuel	Enriched uranium	MOX	Enriched uranium	Plutonium, Natural uranium	Plutonium	Enriched uranium
Fuel enrichment	30%	25%	93%	23%	(92% fissile Pu)	2.6%
Diluent material or Moderator	Sodium	Sodium	Graphite	Sodium	Stainless steel	Water
Core dimensions (cm) Radius x Height	48 x 60	50 x 60	33 x 51	36 x 61	35 x 61	9.4 x 92^a
Experimental β_{eff} (pcm)	716 ±2.3%	343 ±2.0%	742 ±3%	364 ±3%	251 ±2%	771 ±2.2%
C/E of β_{eff}	1.016	1.019	1.003	1.010	0.978	1.024

[a] Critical water level

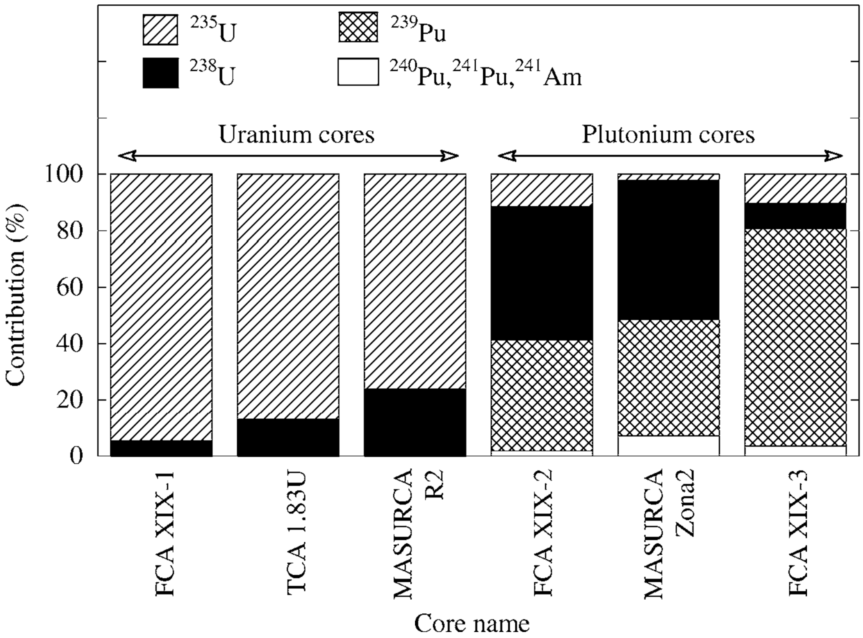
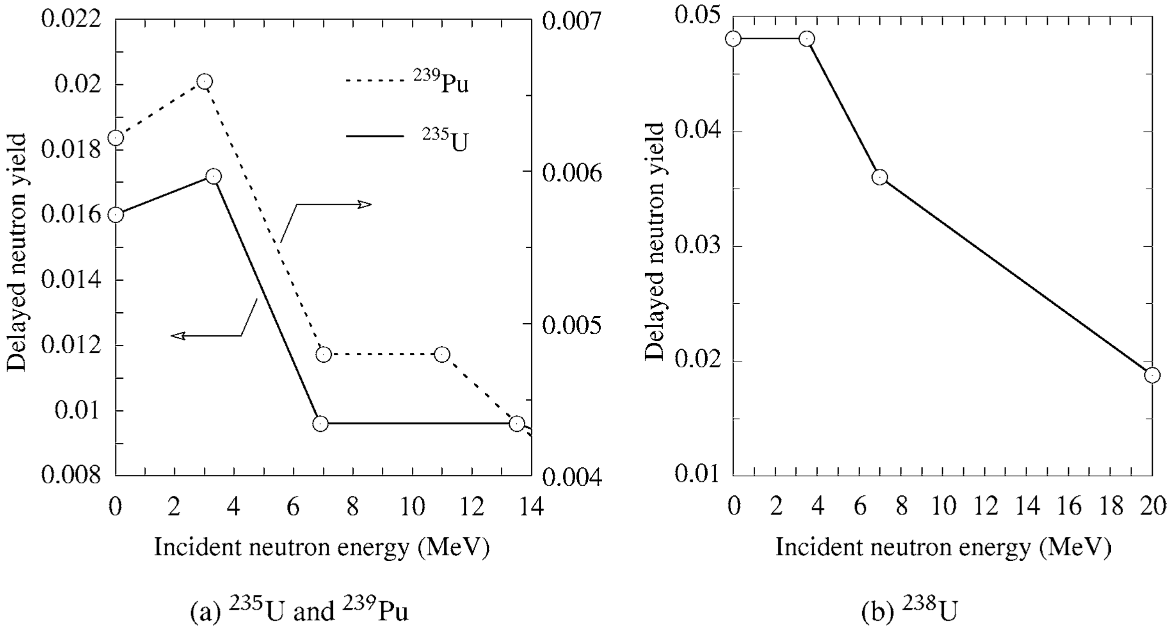


Figure 1. Nuclide contributions to β_{eff} of benchmark cores.



(a) ^{235}U and ^{239}Pu (b) ^{238}U

Figure 2. Delayed neutron yields of principal nuclides in JENDL-3.2.

2.2 DATA AND METHODS FOR ADJUSTMENT

The adjustment was carried out on the yields given at several energy points in the file. The adjusted delayed neutron yields and their covariances are given by

$$\mathbf{P}' = \mathbf{P} + \mathbf{Q}\mathbf{S}^{\mathbf{tr}}\left[\mathbf{S}\mathbf{Q}\mathbf{S}^{\mathbf{tr}} + \mathbf{G}\mathbf{M}\mathbf{G}^{\mathbf{tr}} + \mathbf{V}_e + \mathbf{V}_{\mathbf{m}}\right]^{-1}\left[\mathbf{R}_e - \mathbf{R}_c\right], \quad (2)$$

$$\mathbf{Q}' = \mathbf{Q} - \mathbf{Q}\mathbf{S}^{\mathbf{tr}}\left[\mathbf{S}\mathbf{Q}\mathbf{S}^{\mathbf{tr}} + \mathbf{G}\mathbf{M}\mathbf{G}^{\mathbf{tr}} + \mathbf{V}_e + \mathbf{V}_{\mathbf{m}}\right]^{-1}\mathbf{S}\mathbf{Q}, \quad (3)$$

where

$\mathbf{P}, \mathbf{P}'$: Column vectors with elements that are the original and the adjusted delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu, respectively,

$\mathbf{Q}, \mathbf{Q}'$: Covariance matrixes of the original and the adjusted delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu, respectively,

$\mathbf{S}$: A matrix whose elements are the sensitivity coefficients of β_{eff} to the delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu,

$\mathbf{M}$: Covariance matrixes of cross sections other than the delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu,

$\mathbf{G}$: A matrix whose elements are the sensitivity coefficients of the β_{eff} to the cross sections other than the delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu,

$\mathbf{V}_e$: A covariance matrix of the experimental β_{eff},

$\mathbf{V}_{\mathbf{m}}$: A covariance matrix of the calculated β_{eff} which is ascribed to the uncertainty in calculation method of β_{eff},

$\mathbf{R}_e, \mathbf{R}_c$: Column vectors whose elements are the experimental and the calculated values of β_{eff}, respectively.

The superscript $\mathbf{tr}$ stands for a transpose of the matrix.

The energy dependence of the yield between the energy points, which is given by the linear interpolation in the JENDL-3.2 file, was taken into account in calculating the sensitivity matrix $\mathbf{S}$. It was found from this sensitivity analysis that β_{eff} had large sensitivities to the ν_d values of ^{235}U and ^{239}Pu at the thermal energy point even in the fast reactor cores fueled with uranium and plutonium, respectively. On the other hand, the β_{eff} had small sensitivities to the ν_d values of these nuclides at the other energy points.

The matrixes $\mathbf{Q}$ and $\mathbf{M}$ were based on the JENDL-3.2 covariance file[10], where no correlations were given between the delayed neutron yields of the three nuclides and the neutron cross sections. The delayed neutron yields of the three nuclides therefore were assumed to be statistically independent of the cross sections as shown in these equations and the adjustment was made solely for the yields. For the delayed neutron spectra, the covariance was not available. Hence the covariance of calculated β_{eff} that was ascribed to the uncertainty of the spectra was estimated from a variation of β_{eff} that resulted from changing the spectra. The estimated covariance was added to the matrix $\mathbf{V}_{\mathbf{m}}$. The covariance matrix of experimental β_{eff}, $\mathbf{V}_e$, was calculated from experimental errors given in Refs.[1,2,8,9], which are also shown in Table I. No correlation of β_{eff} values between the different cores was considered.

Figure 3 presents variances of calculated β_{eff} and their breakdowns in sources of uncertainty. This figure shows that dominant contributions come from the variances caused by the uncertainty of delayed neutron yields of principal nuclides. It is therefore more efficient to adjust these yields than to adjust the other nuclear data for achieving better prediction accuracy of β_{eff}. This supports the adjustment made solely for these yields by using Eqs.(2) and (3). For the adjustments of group constants other than the delayed neutron yields, it is appropriate to use many kinds of integral data collected from wide variety of critical experiments. Such adjustments are not within the scope of present work. Detailed descriptions on the calculation of sensitivity coefficients and the preparation of covariance matrixes are shown in Ref.[19].

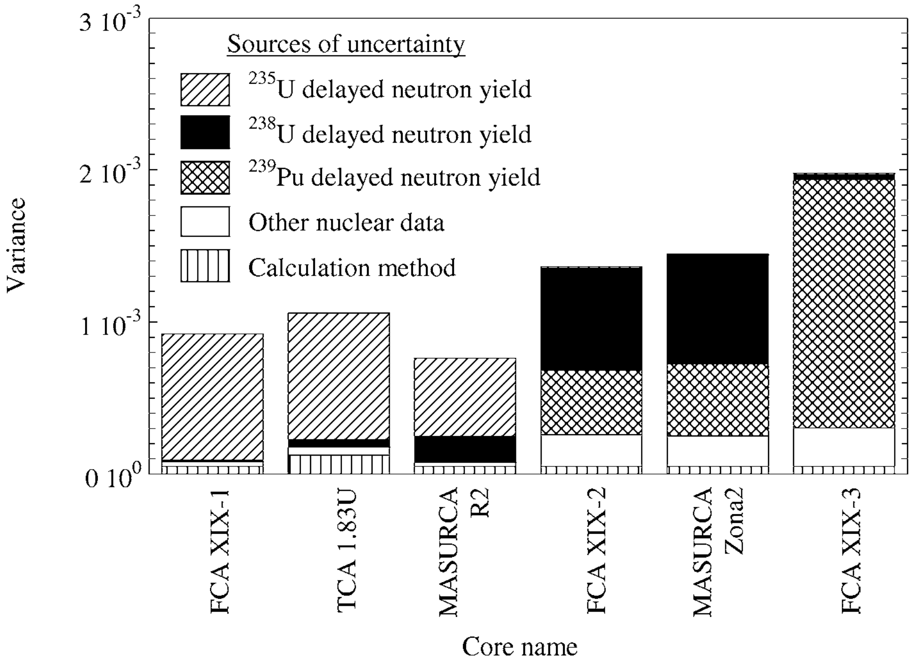


Figure 3. Variance of calculated β_{eff} before adjustment of delayed neutron yields. Breakdown of variance in sources of uncertainty is also shown.

2.3 RESULTS OF ADJUSTMENTS

The adjusted delayed neutron yields are compared with the original yields of JENDL-3.2 in Table II. Relative changes of yields by the adjustment are also shown in this table. It is noted that these changes are within uncertainty bounds of the yields before the adjustment.

For ^{238}U, the yields are decreased almost uniformly by about 3% at energy points below 7 MeV. This uniform change is caused by the large correlations of yields between energy points below 7 MeV. The yield is increased by 2.1% at 20 MeV although the sensitivity is negligibly small at this energy point. This increase is caused by a negative correlation of yields between this energy point and the others. Figure 4(a) compares the adjusted yield with those in three major evaluated nuclear data files of the JENDL-3.2, ENDF-B/VI and JEF-2.2[20]. The original yield of JENDL-3.2 takes a value of 0.0481 below 3.5 MeV. The yield of JEF-2.2 and that of JENDL-3.2 take the identical value. The yield of ENDF-B/VI takes a value of 0.044 below 4 MeV. The yield of Tuttle's evaluation, which has been widely used in nuclear industry, takes a value of 0.0439 which is very close to that of ENDF/B-VI below 4 MeV. The discrepancy of about 9% is found for the yields between (a) JENDL-3.2 and JEF-2.2 (0.0481) and (b) ENDF/B-VI and Tittle (about 0.044). The adjustment resulted in a yield value of 0.0466 below 3.5 MeV, which is close to a mean of (a) and (b).

For ^{239}Pu, an increase of yield by 2.6% is observed at the thermal energy point, while a small change of less than 0.3% is found at the other energy points. The large change of yield at the thermal energy point is ascribed to the large sensitivity at this energy point as discussed in section 2.2. Figure 4(b) compares the adjusted yield with those in three nuclear data files. The adjusted yield is close to that of ENDF/B-VI below 1 MeV.

Table II. Comparison of original delayed neutron yield in JENDL-3.2 and adjusted yield for principal nuclides

(a) ^{235}U

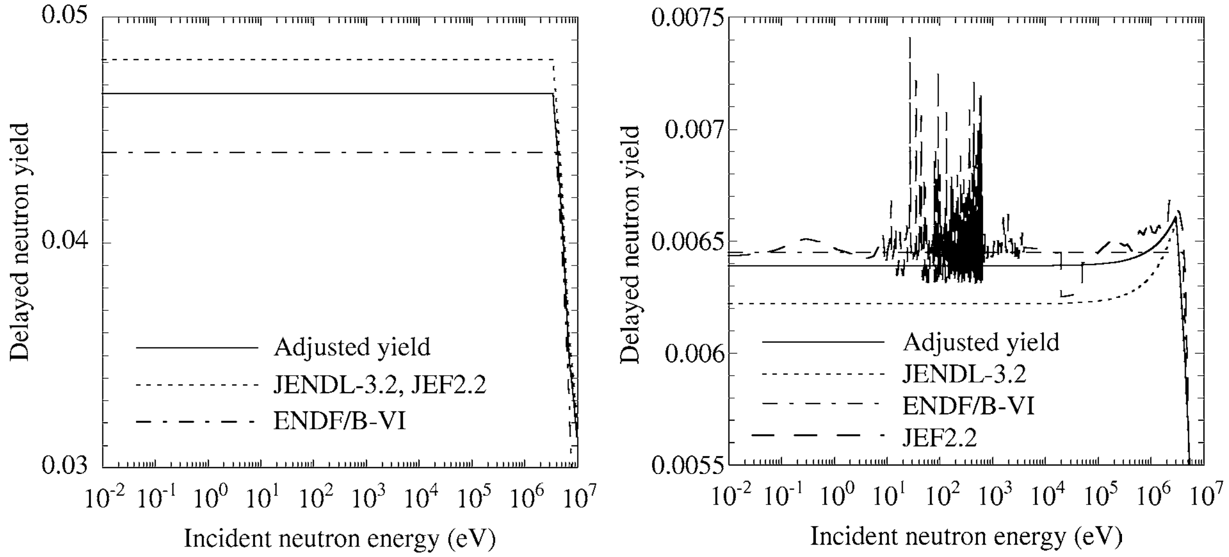
	Energy points			
Item	Thermal	3.3MeV	6.9MeV	13.5MeV
Original yield	0.01600±3.3%	0.0171875±6.1%	0.0096±10.1%	0.0096±8.0%
Adjusted yield	0.01586±1.8%	0.01717±5.7%	0.0096±10.1%	0.0096±8.0%
Relative change of yield (%)	-0.90	-0.11	-0.04	-0.01

(b) ^{238}U

	Energy points			
Item	Thermal	3.5MeV	7MeV	20MeV
Original yield	0.0481±5.4%	0.0481±5.4%	0.036±6.6%	0.0188±10.5%
Adjusted yield	0.0466±3.6%	0.0466±3.6%	0.035±5.0%	0.0192±10.2%
Relative change of yield (%)	-3.08	-3.08	-3.32	2.08

(c) ^{239}Pu

	Energy points			
Item	Thermal	3MeV	7MeV	11MeV
Original yield	0.00622±6.5%	0.00659±4.0%	0.0048±4.0%	0.0048±4.0%
Adjusted yield	0.00638±3.6%	0.00661±4.0%	0.0048±4.0%	0.0048±4.0%
Relative change of yield (%)	2.58	0.24	0.00	0.00



(a) ^{238}U (b) ^{239}Pu

Figure 4. Comparison of adjusted delayed neutron yield with evaluated ones in JENDL-3.2, ENDF/B-VI and JEF-2.2 for ^{238}U and ^{239}Pu.

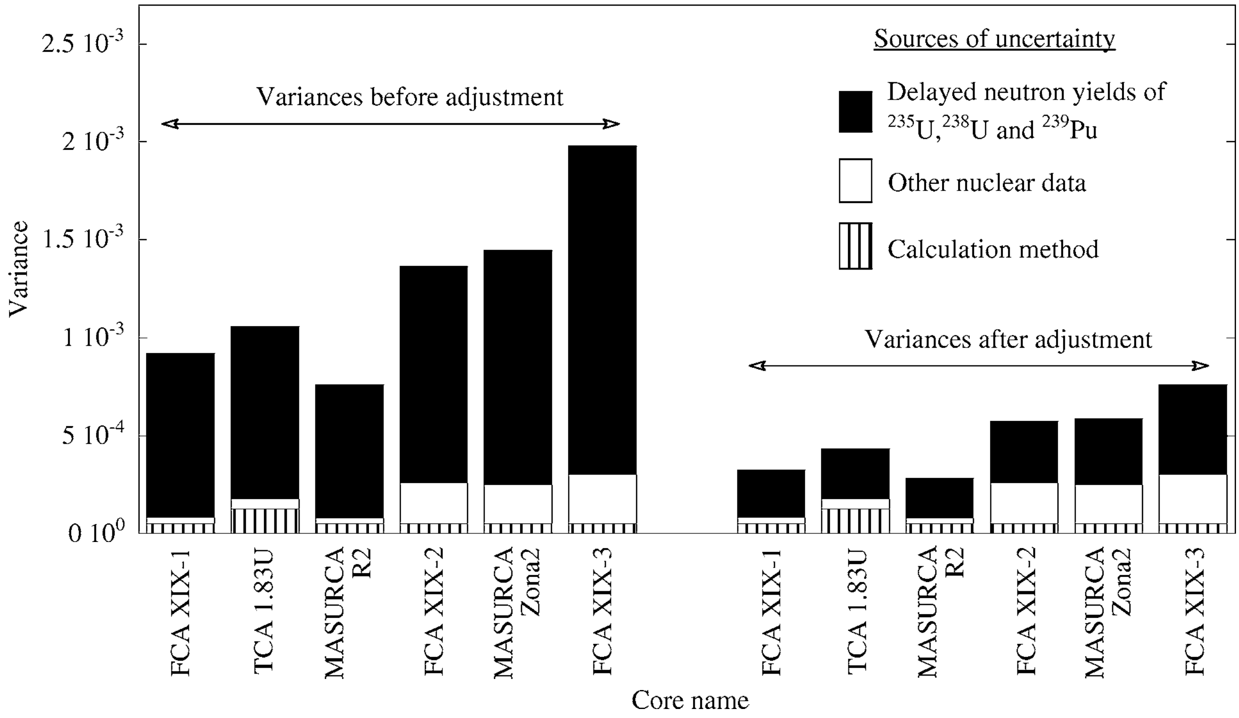


Figure 5. Comparison of variance of calculated β_{eff} between before and after adjustment. Breakdowns of the variance in sources of uncertainty are also shown. The uncertainties of delayed neutron yields of principal nuclides and those of other sources are considered independently in the adjustment.

The change of yield of ^{235}U is less than those for ^{238}U and ^{239}Pu. The yield of ^{235}U is decreased by 0.9% at the thermal energy point. The change is less than 0.3% at the other energy points.

Standard deviations are also compared between the original and adjusted yields in Table II. For ^{238}U, a considerable reduction is observed for the standard deviations at energy points below 7 MeV. For ^{235}U and ^{239}Pu, a significant reduction of standard deviations is observed solely at the thermal energy point. Figure 5 compares the variances of calculated β_{eff} between before and after the adjustment. Breakdowns of the variances in sources of uncertainty are also shown in this figure. Notable reductions by a factor of 3~4 are observed for the variances after the adjustment. This was brought by both (a)the reduction of standard deviations of yields and (b)negative correlations of yields between different nuclides which were introduced by the adjustment. Table III compares the C/E values of β_{eff} of the benchmark cores before and after the adjustment of yields. The improvement of C/E values by the adjustment can be observed.

Table III. C/E values of β_{eff} of benchmark cores before and after adjustment of delayed neutron yields

	MASURCA cores		FCA cores			TCA core
Item	R2	Zona2	XIX-1	XIX-2	XIX-3	1.83U
C/E before adjustment	1.016	1.019	1.003	1.010	0.978	1.024
C/E after adjustment	1.003	1.012	0.994	1.002	0.990	1.012

3. VALIDATION OF ADJUSTED DELAYED NEUTRON YIELDS BY ANALYSES OF β_{eff} EXPERIMENTS AT ZPR ASSEMBLIES

Analyses were carried out for the β_{eff} experiments at three plutonium fueled cores and three uranium fueled cores built in ZPR fast critical facility for the validation of the adjusted delayed neutron yields. Table IV shows major characteristics of these cores. These cores were also simple in geometry. The core-region was surrounded by blanket-region and/or reflector-region of stainless steel. Figure 6 shows nuclide contribution to the β_{eff} of these cores.

The analyses were carried out by using the 70-energy-group constants set JFS-3-J3.2, the adjusted delayed neutron yields and the delayed neutron spectra of ENDF/B-VI. Effective cross sections of each region in these cores were prepared by a collision probability code with heterogeneous compositions of fuel cells. The forward and adjoint fluxes in these cores were calculated by a transport theory code in a two-dimensional cylindrical geometry. Moreover, the original delayed neutron yields of JENDL-3.2 were also used in these analyses for a comparison purpose.

Table IV. Major characteristics of ZPR cores

Item	Core name: Reference U/Fe	Leak U/Fe	U9	Carbide Benchmark	RSR	Pu/C/SS
Fuel	Enriched uranium	Enriched uranium	Enriched uranium, Depleted uranium	Plutonium, Depleted uranium	Plutonium, Depleted uranium	Plutonium
Fuel enrichment	93%	93%	9%	14%	25%	(95% fiss -ile Pu)
Diluent material or Moderator	Iron	Iron		Sodium, Graphite	Sodium, Iron	Stainless steel, Graphite
Core dimensions (cm) Radius x Height	63 x 183	63 x 183	41 x 76	59 x 92	44 x 92	42 x 76
Experimental β_{eff} (pcm)	667 ±2%	662 ±2%	706 ±2%	381 ±2%	335 ±2%	222 ±2%

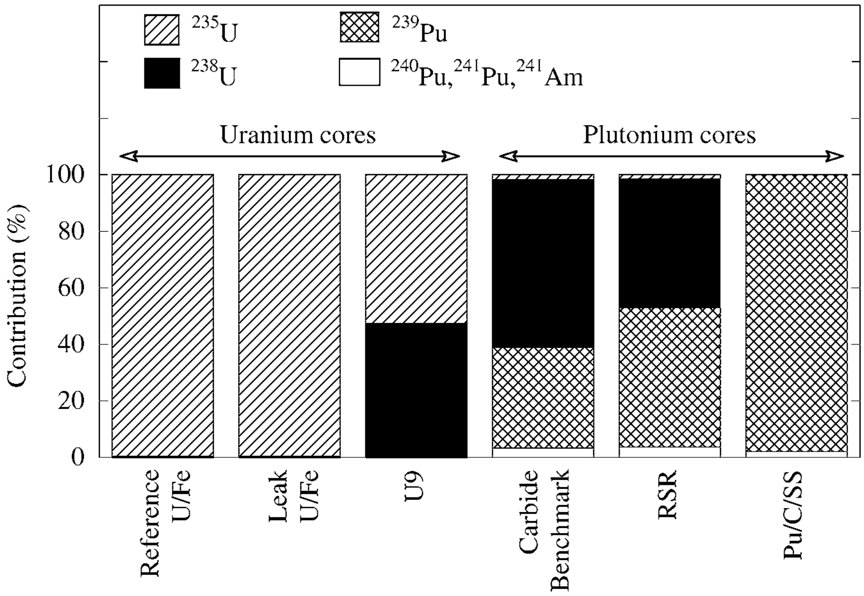


Figure 6. Nuclide contributions to β_{eff} of ZPR cores.

Table V compares the C/E values of β_{eff} between the original yields of JENDL-3.2 and the adjusted yields. For two cores of U9 and Pu/C/SS, the calculated β_{eff} values change by about 2% through the adjustment and the C/E values are improved by using the adjusted yields. For the other cores, the change of calculated β_{eff} values is found to be almost within 1% between original and adjusted yields. The calculated β_{eff} values with both original yields and adjusted ones are in good agreement with the experimental β_{eff} value in three cores of Reference U/Fe, Leak U/Fe and Carbide Benchmark. On the other hand, the adjusted yields does not reduce the deviation of β_{eff} between calculation and experiment in the RSR core.

Table V. C/E values of β_{eff} of ZPR cores with original delayed neutron yields of JENDL-3.2 and adjusted yields

	Core name					
Item	Reference U/Fe	Leak U/Fe	U9	Carbide Benchmark	RSR	Pu/C/SS
C/E with original yields of JENDL-3.2	0.994	1.002	1.033	1.009	0.978	0.966
C/E with adjusted yields	0.986	0.994	1.013	0.998	0.974	0.988

4. CONCLUSIONS

The cross section adjustment method was applied to the total delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu in the JENDL-3.2 file by using the C/E values of β_{eff} of six benchmark cores built in the critical facilities of MASURCA, FCA and TCA. The adjustment was carried out on the yields given at several energy points in the file. The energy dependence of yield between these energy points, which has been given by the linear interpolation in the file, was taken into account in calculating the sensitivities for the adjustment.

As the result of adjustment, the yields of ^{238}U were uniformly decreased by about 3% at energy points below 7 MeV. The adjusted yield of this nuclide is 0.0466 below 3.5 MeV. For ^{235}U and ^{239}Pu, the adjustment made a significant change of yield solely at the thermal energy point. This result was caused by the large sensitivity of β_{eff} to the yield at the thermal energy point and the small ones at the other energy points for two nuclides. The yield of ^{239}Pu was increased by 2.6%, while that of ^{235}U was decreased by 0.9% at this energy point. These adjusted yields improved the agreement of β_{eff} between experiment and calculation not only in the cores of MASURCA, FCA and TCA but also in several cores of ZPR. Furthermore, the adjustment reduced the standard deviations of yields and introduced the negative correlations of yields between different nuclides, which brought the reduction of uncertainty of calculated β_{eff}. These adjusted yields are recommended for the β_{eff} calculation.

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