Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 2, p. 136–139 (August 2002)

Evaluation of Delayed Neutron Data for JENDL-3.3

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Delayed neutron data of ^{235}U, ^{238}U and ^{239}Pu have been evaluated and recommended for JENDL-3.3. Adjustment of ν_d was carried out on the basis of the $\beta_{\rm eff}$ measurements at FCA, MASURCA and TCA using the JENDL-3.2 data as the initial guess. Through this adjustment the ν_d value for ^{238}U below 3.5 MeV was decreased by about 3 % from 0.0481 to 0.0466. The ν_d values of ^{235}U and ^{239}Pu were also determined in this way. Further appropriate six group constants, the decay constants λ_i and the group yields α_i, were determined from experimental data of the delayed neutron emission rates, which were collected and compiled by Spriggs through the SG6 activity of WPEC. Applicability of the resultant group constants was validated through the analyses of the reactivity measurements based on the period or the rod-drop methods.

KEYWORDS: delayed neutron fraction, beta effective, reactivity scale, delayed neutron spectra

I. Introduction

The delayed neutron emission following fission is an extremely significant phenomenon in the control of nuclear reactors and in the interpretation of the reactivity effects in reactors and critical facilities. In this respect, delayed neutron data are included in the Japanese Evaluated Nuclear Data Library, JENDL, and other major nuclear data libraries. It consists of the yield per fission ν_d, the temporal group constants λ_i and α_i (i=1,N), and the energy spectra χ_d^i(E), where the number N is taken to be six traditionally. Any thorough and systematic preview, however, had not been conducted on the inclusion of the data into JENDL up to the revision 3.2. This was the case although there had been an important activity of measuring the effective delayed neutron fraction, $\beta_{\rm eff}$, in the FCA facility of Japan Atomic Energy Research Institute(JAERI) in close cooperation with MASURCA group at Commissariat a l'Energie Atomique(CEA), France.

In April 1997 the Delayed Neutron Working Group (DNWG) was established within the Japanese Nuclear Data Committee to fill this apparent gap and to provide an opportunity to improve the delayed neutron data through the cooperation between the nuclear data people and the reactor physics people including the FCA group. In July 1997 the Heavy Nuclide Data Evaluation Working Group (HNDEWG) requested DNWG to recommend the delayed neutron data for inclusion in JENDL-3.3. DNWG responded to it with the following principles. 1) The recommendation is to be made for ν_d, λ_i, α_i and χ_d^i(E) of three major nuclides ^{235}U, ^{238}U and ^{239}Pu. 2) The $\beta_{\rm eff}$ data is to be critically previewed through the analyses of the measurement at FCA, MASURCA and TCA thermal critical facility of JAERI. 3) Effect of the revision of λ_i and α_i data is to be evaluated through the reactor period calculation of TCA, VHTRC of JAERI and commercial reactors. 4) Six-group temporal representation (N=6 in the above expression) is to be kept for technical continuity.

In Chapter II the ν_d data assessment based on the adjustment will be described. Chapters III and IV deal with the λ_i, α_i data and χ_d^i(E), respectively.

II. Delayed Neutron Yield

Total delayed neutron yields ν_d of ^{235}U, ^{238}U and ^{239}Pu are the most important nuclear data for the calculation of $\beta_{\rm eff}$. There are, however, discrepancies of the yields between major evaluated nuclear data libraries. For instance, a significant discrepancy of 9 % is found for the yield of ^{238}U between JENDL-3.2 and ENDF/B-VI as shown in **Fig. 1**. In a typical fast reactor, the contribution of ^{238}U to $\beta_{\rm eff}$ reaches 50 %.[1)] These features cause a variation of $\beta_{\rm eff}$ of up to 5 % when the yield of ^{238}U in one evaluation is replaced with that in the other evaluation. It is therefore useful to recommend the yields with more reliability by using results of integral experiments.

The cross section adjustment method was applied for the JENDL-3.2 delayed neutron yields of ^{235}U, ^{238}U and ^{239}Pu by using the C/E values of $\beta_{\rm eff}$ benchmark experiments performed at two cores fueled with uranium and three cores fueled with plutonium in two fast critical facilities, MASURCA of CEA and FCA of JAERI, and a core fueled with uranium in TCA of JAERI. The details of adjustments are given in reference.[2)] The present paper briefly summarizes the method and

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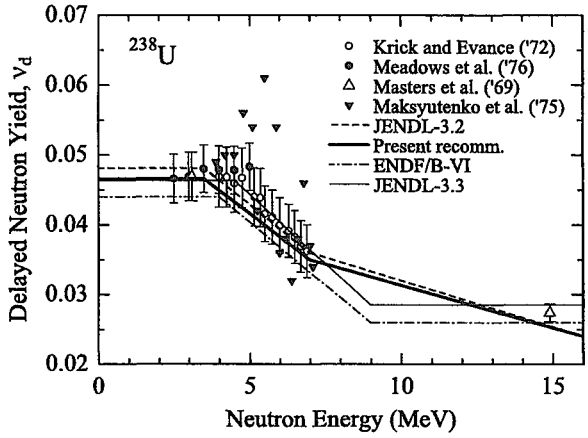

Fig. 1 Energy dependence of ^{238}U delayed neutron yields

the results of adjustment.

In the JENDL-3.2 file, the yields are given at several incident neutron energy points as shown in **Table 1**. It is specified that the yields between these points are obtained by linear interpolation. The adjustment was carried out on the yields given at these energy points. The adjusted delayed neutron yields and their covariances are given by

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

$$\boldsymbol{Q}' = \boldsymbol{Q} - \boldsymbol{Q}\boldsymbol{S}^{tr}\left[\boldsymbol{S}\boldsymbol{Q}\boldsymbol{S}^{tr} + \boldsymbol{G}\boldsymbol{M}\boldsymbol{G}^{tr} + \boldsymbol{V}_e + \boldsymbol{V}_m\right]^{-1} \times \boldsymbol{S}\boldsymbol{Q}, \quad (2)$$

where

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

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

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

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

$\boldsymbol{G}$: 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,

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

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

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

The superscript tr stands for a transpose of the matrix.

The matrixes $\boldsymbol{Q}$ and $\boldsymbol{M}$ were based on the JENDL-3.2 covariance file,[3] 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 $\boldsymbol{V}_m$.

The energy dependence of the yield between the energy points, which is given by the linear interpolation in the file, was taken into account in calculating the sensitivity matrix $\boldsymbol{S}$. 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 which are above 3 MeV.[2]

Table 1 Comparison of original delayed neutron yield in JENDL-3.2 and adjusted yield for ^{235}U, ^{238}U and ^{239}Pu

(a) ^{235}U

Item	Energy points			
	Thermal	3.3MeV	6.9MeV	13.5MeV
Original yield	0.01600 ±3.3%	0.01719 ±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

Item	Energy points			
	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

Item	Energy points			
	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

The adjusted delayed neutron yields are compared with the original yields of JENDL-3.2 in Table 1. Relative changes of the 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. As the result of the adjustment, the yields of ^{238}U were uniformly decreased by about 3 % at energy points below 7 MeV. This uniform change is caused by large correlations of the yields between the 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. The adjusted yield of this nuclide is 0.0466 below 3.5 MeV. As can be seen in Fig.1, the adjusted result (bold solid-line) runs amid the plots of the measured ν_d below 3.5 MeV. Between 3.5 and 7 MeV, however, it is slightly smaller than the measurements. For ^{235}U and ^{239}Pu, the adjustment introduced a 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 as mentioned above. The yield of ^{239}Pu was increased by 2.6 %, while that of ^{235}U was decreased by 0.9 % at this energy point.

Table 2 compares the C/E values of β_{eff} between before and after the adjustment. These adjusted yields improved the agreement of β_{eff} between experiment and calculation. 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}.

III. Six Group Constants

In the course of the working-party activity on delayed neutrons of OECD/NEA, Subgroup 6 of WPEC, Spriggs et al.[4] critically reviewed the experimental data and proposed a set of 8-group delayed neutron constants (λ_i and α_i). DNWG, however, decided to adopt the traditional 6-group representation constants mainly to keep the technical continuity. Then the original 6-group representation of the experimental data, on which the recommended 8-group constants were based, were adopted as the candidate for the JENDL delayed neutron 6 group constants. The ENDF format, however, allows only one set of the half-lives for one fissioning nuclide. This means that, even if different 6-group half-lives are given for different incident energies (thermal, fast or high energy), only the same half-lives are allowed to be adopted for one kind of fissioning system in the JENDL file. Using the original 6-group representations, the temporal dependence of the delayed neutron yields were reproduced and the results were re-fitted with least squares method using one set of fixed half-lives to obtain a new set of 6-group constants. An example of the fitted results is shown in **Table 3** in comparison with the JENDL-3.2 data.

The influence of the change in 6-group constants on reactivity measurement was evaluated numerically. Reactivity was calculated based on the kinetics equation using JENDL-3.2 and the present 6-group constants for some asymptotic periods. Comparison of the reactivity was made for a typical 17 × 17 PWR uranium fuel assembly of 4.1 w/o ^{235}U enrichment and for a MOX fuel assembly of 10 w/o Pu enrichment. The results are shown in Table 4 for the uranium case. **Table 4** shows that the use of present data instead of JENDL-3.2 increases reactivity by 3 % for the asymptotic period at 500 seconds and beyond. For the MOX case, the increase in reactivity for the same period range was 1.5 % at most. A similar study for critical cores, TCA and VHTRC in JAERI, also showed that the measured reactivity by period method or rod drop method increases by about 3 %.

Table 4 Impact of delayed-neutron data on reactivity (Uranium case)
Reactivity (pcm)

Period (s)	JENDL-3.2	Present	Difference (%)
1	538.64	545.05	1.2
2	463.75	470.09	1.4
5	349.63	355.19	1.6
10	263.51	268.20	1.8
20	186.57	190.32	2.0
50	106.20	108.72	2.4
100	63.68	65.37	2.7
200	35.81	36.83	2.8
500	15.59	16.06	3.0
1000	8.04	8.29	3.1

IV. Delayed Neutron Spectra

In JENDL-3.2, the delayed neutron spectra evaluated by Saphier et al.[5] were adopted for ^{232}Th, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu. They made a summation calculation considering 20 precursors. In 1989, Brady and England[6] reported results of new summation calculation, in which 271 precursors were taken into consideration. Basic parameters such as neutron emission probabilities and neutron spectra from precursors were largely improved. After Brady and England, a couple of evaluations were made for the delayed neutron spectra. However, we recommended the results of Brady and England for the main actinides for JENDL-3.3, because they were the most systematic and reliable.

Large discrepancies between two evaluations by Saphier et al. and by Brady and England are seen in the low energy parts of emitted neutrons. The spectra of Saphier et al. are almost zero in the low energy part. Those of Brady and England have no such trends, and seem to be reasonable.

Table 2 C/E values of β_{eff}

Item	MASURCA cores		FCA cores			TCA core
	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% fiss -ile Pu)	2.6%
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

Table 3 Six group constants of ^{235}U

Group No.	Half-lives (λ_i)		Abundance (α_i)					
			Thermal		Fast		High	
	Present	JENDL-3.2	Present	JENDL-3.2	Present	JENDL-3.2	Present	JENDL-3.2
1	1.244E-02	1.27E-02	0.033	0.033	0.035	0.038	0.049	0.057
2	3.054E-02	3.17E-02	0.219	0.219	0.217	0.213	0.176	0.192
3	1.114E-01	1.15E-01	0.196	0.195	0.212	0.188	0.202	0.190
4	3.014E-01	3.11E-01	0.395	0.395	0.385	0.407	0.390	0.357
5	1.136E+00	1.40E+00	0.115	0.115	0.126	0.128	0.115	0.120
6	3.014E+00	3.87E+00	0.042	0.042	0.025	0.026	0.068	0.084

V. Conclusion

At the end of the year 2000 DNWG delivered the recommendation for the ν_d, λ_i, α_i and χ_d^i(E) data of ^{235}U, ^{238}U and ^{239}Pu described here to HNDEWG. They, however, re-evaluated the ν_d values in the whole energy range with the help of the present DNWG adjustment result. This is because there is a rigid principle that JENDL should contain only the microscopically evaluated data and partly because the adjusted result is reliable only in the low energy region where the measured β_{eff}'s have essential sensitivity to ν_d data. In other words, JENDL data can be used as the initial data of adjustment but the JENDL data themselves should not be the adjustment result. Those re-evaluations were basically guided by differential measurement of ν_d, but they found that the new values for ^{235}U and ^{238}U were in good agreement with those obtained by the present adjustment.[7] They kept the ν_d value unchanged from JENDL-3.2 for ^{239}Pu based on the microscopic consideration. The λ_i, α_i and χ_d(E) data were adopted in JENDL-3.3 as recommended by DNWG.

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