Verification of the Evaluated Fission Product Yields Data from the Neutron Induced Fission of ^{235}U, ^{238}U and ^{239}Pu Based on the Delayed Neutron Characteristics

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Abstract. For this case, the microscopic characteristics have been used, such as the cumulative yields of fission products, the probabilities of delayed neutron emission and the half-lives of their precursors. As a result for each database of the cumulative yields of fission products four values of the absolute total delayed neutrons yields ν_d and four values of the average half-life of delayed neutron precursors $<T_{1/2}>$ were obtained. For each combination of data sets "CY – (P_n,$T_{1/2}$)" a model curve of delayed neutron activity was calculated for the ^{235}U(n_{th},f) reaction. The analysis of the results based on the comparison of the obtained delayed neutron macroscopic parameters ν_d and $<T_{1/2}>$ with the appropriate evaluated data allowed to study the sensitivity of the macroscopic delayed neutron parameters (ν_d, $T_{1/2}$) to the microscopic delayed neutron data sets (P_n,$T_{1/2}$) for each of the considered fission reactions.

Key Words: Delayed neutrons, fission products, average half-lives, total yields.

1. Introduction

Traditionally the summation method [1] is used for calculation such characteristics of delayed neutrons as the total delayed neutron yield ν_d, the relative abundances a_i, the half-lives T_i and the energy spectra of separate groups of delayed neutrons. In the present work, we consider additional macroscopic parameter – the average half-life of delayed neutron precursors $<T_{1/2}>$. This parameter unequivocally characterizes the fissioning system and follows the systematics on the nucleon content and the excitation energy of the fissioning compound nucleus [2].

The summation method is based on the data on the cumulative yields of fission products (CY), the emission probabilities of delayed neutron (P_n) and the half-lives of their precursors ($T_{1/2}$). These data are being constantly improved in the process of accumulation of new experimental data and improvement of the theoretical and systematics approaches used for their estimation [3]. The accuracy of the summation method used for calculation of the aggregate delayed neutron parameters is now comparable with the accuracy of experimental methods. Therefore it is obvious that in case of low sensitivity of the calculated DN parameters to the (P_n,$T_{1/2}$) data sets the summation method can be used for the determination of the most reliable database on the fission product yields which are presented in ENDF/B, JEFF, JENDL, ROSFOND libraries.

The objective of this work is the comparative analysis of the delayed neutron macroscopic characteristics for the thermal and the fast neutron induced fission of ^{235}U, ^{238}U and ^{239}Pu obtained by the summation method on the basis of existing databases on the fission product yields presented in the last version of ENDF/B, JEFF, JENDL, ROSFOND libraries and various sets on the microscopic delayed neutron data (P_n,$T_{1/2}$). This analyses allows study the sensitivity of the macroscopic delayed neutron data ν_d and $<T_{1/2}>$ to the microscopic delayed neutron data sets (P_n,$T_{1/2}$) for each of the considered fission reactions. Comparison of the obtained data with the relevant evaluated experimental data, in turn, allows conclusions to be made on the fission product yields and microscopic data set (P_n,$T_{1/2}$) from the standpoint of their best agreement with the aggregate delayed neutron parameters ν_d and $<T_{1/2}>$.

2. Verification of the databases of the fission product yields on the basis of the total DN yield calculations.

The total delayed neutron (DN) yield was calculated according to the following formula $\nu_d = \sum_i CY_i \cdot P_{ni}$, where CY_i – the cumulative yield of i-th DN precursor, P_{ni} – the probability of delayed neutron emission by i-th precursor. Summation was made over all precursors presented in the appropriate data set.

The cumulative yields of 368 DN precursors from the JEFF-3.1.1, ENDF/B-VII.1, JENDL-4.0, ROSFOND-2010 libraries [4] and the evaluated data by Wahl [5] were used as the basic input data. Four data sets on the probabilities of the delayed neutron emission P_{ni} and half- lives of their precursors $T_{1/2}$ were used: the set obtained on the basis of the Kratz-Herrmann systematic [6] (in the text: P-K-M), the evaluated experimental data [7] (in the text: Rudstam), the evaluation on the basis of experimental data and systematics [8] (in text: E-W), and data obtained in the Nuclear data section of the IAEA on the basis of all experimental data known to 2010 [9] (in the text: IAEA). Currently, we have not tested the P_n data set obtained on the basis of the systematics studies [10].

The results on the total DN yields for the thermal and fast neutron induced fission of ^{235}U, ^{239}Pu and the fast neutron induced fission of ^{238}U are presented in Tables 1-5 together with the recommended data [11], summation calculations on the basis of the JEF-2.2 [1] and the ENDF/B-VI library [8]. These data are also plotted in the FIGS. 1-2. The uncertainties $d\nu_d$ are calculated only for P_n taken from the IAEA data set [9]. The obtained values of the uncertainties are typical for the summation method and therefore they can be extended to all other cases presented in Tables 1-5.

The recommended data on the total delayed neutron yields have been chosen by Subgroup 6 of the OECD NEANSC Working Party on International Evaluation Cooperation in 2002. It should be noted that the recommended data [11] did not give uncertainties. Therefore, the uncertainties for the recommended data were taken from the previous evaluation [12].

Table 1. The total delayed neutron yields from the thermal neutron induced fission of ^{235}U.

Set $P_n, T_{1/2}$	ν_d, *neutr./100 fiss.*					Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	Wahl [5]	ROSFOND-2010	[11] Recommended data	[1] CY-JEF2.2, Pn-JEF2.2	[8] CY-ENDF/B-VI, Pn-E-W
E-W	1.88	1.88	1.61	1.70	1.61	1.62±0.05	1.71±0.11	1.67
P-K-M	1.93	1.94	1.63	1.72	1.63			-
Rudstam	1.84	1.84	1.61	1.69	1.61			-
IAEA	1.90±0.10	1.91±0.10	1.63±0.08	1.71	1.63±0.08			-

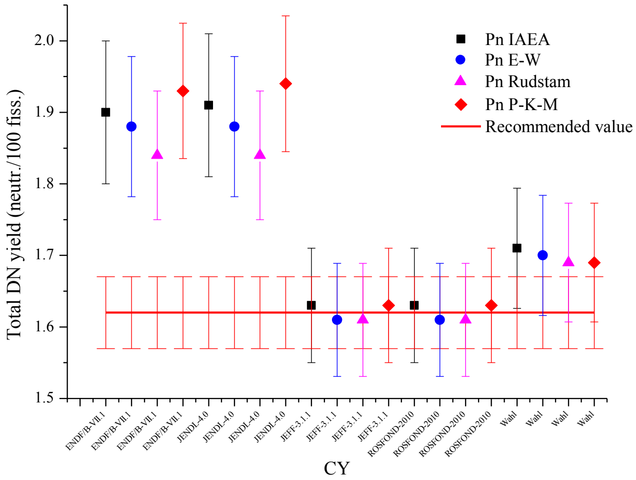

FIG. 1. The total DN yield related to the specific CY database for all P_n sets from the thermal neutron induced fission of ^{235}U.

Table 2. The total delayed neutron yields for the fast neutron induced fission of ^{235}U.

Set (P_n,$T_{1/2}$)	ν_d, *neutr./100 fiss.*				Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	ROSFOND-2010	[11] Recommended data	[1] CY-JEF2.2, Pn-JEF2.2	[8] CY-ENDF/B-VI, Pn-E-W
E-W	1.79	1.81	1.82	1.82	1.63±0.03	1.91±0.13	1.79
P-K-M	1.82	1.93	1.82	1.82			-
Rudstam	1.76	1.78	1.81	1.81			-
IAEA	1.83±0.12	1.85±0.12	1.83±0.09	1.83±0.09			-

Table 3. The total delayed neutron yields for the fast neutron induced fission of ^{238}U.

Set (P_n,$T_{1/2}$)	ν_d, *neutr./100 fiss.*					Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	Wahl [5]	ROSFOND-2010	[11] Recommended data	[1] CY-JEF2.2, Pn-JEF2.2	[8] CY-ENDF/B-VI, Pn-E-W
E-W	4.20	4.21	4.46	4.37	4.20	4.65±0.11	4.31±0.25	4.19
P-K-M	4.35	4.35	4.60	4.53	4.35			-
Rudstam	4.02	4.03	4.24	4.12	4.02			-
IAEA	4.17±0.28	4.18±0.28	4.43±0.15	4.36	4.17±0.28			-

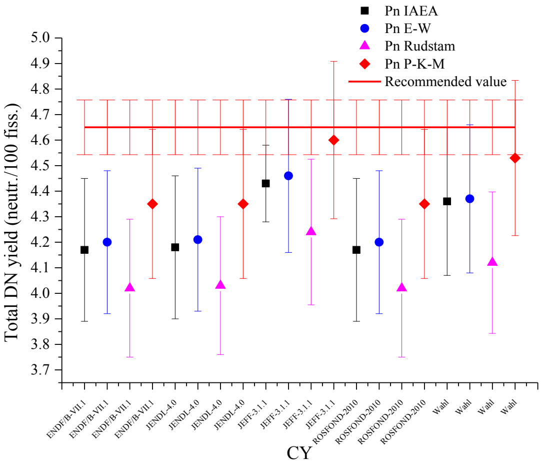

FIG. 2. The total DN yield related to the specific CY database for all P_n sets from the fast neutron induced fission of ^{238}U.

Table 4. The total delayed neutron yields from the thermal neutron induced fission of ^{239}Pu.

Set (P_n,$T_{1/2}$)	ν_d, *neutr./100 fiss.*					Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	Wahl [5]	ROSFOND-2010	[11] Recommended data	[1] CY-JEF2.2, Pn-JEF2.2	[8] CY-ENDF/B-VI, Pn-E-W
E-W	0.74	0.76	0.66	0.70	0.74	0.65±0.04	0.62±0.06	0.74
P-K-M	0.75	0.77	0.65	0.71	0.75			-
Rudstam	0.73	0.75	0.64	0.69	0.73			-
IAEA	0.75±0.03	0.77±0.04	0.66±0.05	0.71	0.75±0.03			-

Table 5. The total delayed neutron yields for the fast neutron induced fission of ^{239}Pu.

Set (P_n,$T_{1/2}$)	ν_d, *neutr./100 fiss.*				Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	ROSFOND-2010	[11] Recommen-	[1] CY-JEF2.2,	[8] CY-ENDF/B-VI

					ded data	Pn-JEF2.2	P_n-E-W
E-W	0.65	0.68	0.73	0.65	0.651±0.016	0.69±0.06	0.65
P-K-M	0.65	0.68	0.72	0.66			-
Rudstam	0.64	0.66	0.71	0.65			-
IAEA	0.66±0.06	0.68±0.07	0.73±0.05	0.66±0.06			-

The data presented in Tables 1-5 allow to estimate the sensitivity of the DN parameter ν_d calculated with a particular CY database and P_n data set. For this purpose the minimum and maximum of the ν_d values obtained for the CY data from the separate library for one of the considered fission reactions with all of the sets of the P_n data were used – $d\nu_d(P_n)/\nu_d = (\nu_d\ max-\nu_d\ min)/\nu_d\ min$. The obtained results are presented in Table 6.

Table 6. The sensitivity of the ν_d values to the individual P_n data sets.

CY database	$d\nu_d(P_n)/\nu_d = (\nu_d\ max-\nu_d\ min)/\nu_d\ min$, %				
	^{235}U(n_{th},f)	^{235}U(n_f,f)	^{238}U(n_f,f)	^{239}Pu(n_{th},f)	^{239}Pu(n_f,f)
ENDF/B-VII.1	3.3	4.0	8.2	2.7	3.1
JENDL-4.0	3.8	8.4	7.9	2.7	3.0
JEFF-3.1.1	1.2	1.1	8.5	3.1	2.8
Wahl	1.2	-	9.9	2.9	-
ROSFOND-2010	1.2	1.1	8.2	2.7	1.5

From the example of the JEFF library, it is seen that for the case of ^{235}U fission by both thermal and fast neutrons the influence of separate sets of P_n is insignificant ($d\nu_d/\nu_d \approx 1.1$-1.2%). While for the fast neutrons induced fission of ^{238}U the calculated value ν_d strongly depends on the set of P_n ($d\nu_d(P_n)/\nu_d = 8.5\%$). This fact indicates that in the case of ^{238}U another group of precursors begins to play role in forming the total DN yield. The large sensitivity of the ν_d values for ^{238}U can be explained by large discrepancies in the different sets of the P_n data for this less investigated group of precursors. The assessment of the most reliable sets of P_n and *CY*, apparently, can be obtained from the comparison of the calculated values ν_d with appropriate-evaluated data. Let us analyze each of the considered fission reactions.

2.1. Reaction ^{235}U(n,f)

From Table 1 it is seen that the cumulative yields CY from the JEFF and ROSFOND libraries give value of ν_d which is the closest to the recommended one – 1.62±0.05 neutr./100 fiss. [11]. The CY data from ENDF/B and JENDL libraries give the overestimated values of ν_d for all sets of P_n as compared with the recommended data ν_d. This shows that the fission product yields from the JEFF library for the ^{235}U(n_{th},*f*) reaction are preferable.

For the ^{235}U(n_{fast},*f*) reaction (Table 2) the *CY* data from JEFF, ENDF/B, ROSFOND and JENDL libraries give ν_d values which are almost identical for all sets of P_n *(low sensitivity of ν_d to P_n data set)*. This fact is the direct indication on the identity of the fission products yields for the ^{235}U(n_{fast},*f*) reaction presented in the JEFF, ENDF/B, ROSFOND and JENDL libraries. However the obtained data don't reproduce the energy dependence $\nu_d(E_n)$ recommended in work [11]. The calculated ν_d value for the fast neutron induced fission of ^{235}U varies in the range (1.76-1.93) neutr./100 fiss., that exceeds the recommended value by 8-18%. Agreement of the ν_d for all CY databases can be considered as the indication of more pronounce energy dependence $\nu_d(E_n)$ as compared with the recommended one.

2.2. Reaction ^{238}U(n,f)

Until recently in many works the summation method gave strongly underestimated values ν_d for ^{238}U – up to 3.8 neutr./100 fiss. [13]. The combination of CY from JEFF and P_n set from P-K-M (Pfeiffer et. al., 2002) gives the closest to the recommended ν_d value – 4.60 neutr./100 fiss. This circumstance indicates that products' yields of the ^{238}U(n_{fast},f) reaction from JEFF library gives the most compatible to experiment results and, as well as in the case of reaction ^{235}U(n_{th},f) it is preferable.

It should be also noted, that the ν_d value for ^{238}U(n_{fast},f) underestimated as compared with experiment for the CY databases from ENDF/B, JENDL and ROSFOND (4.35 neutr./100 fiss), showing full correlation of the results obtained using JEFF with all the P_n sets. It is possible to explain by a shift of the most probable charges in isobaric chains of fission fragments. This assumption requires an additional verification.

2.3. Reaction ^{239}Pu(n,f)

In case of the ^{239}Pu(n_{th},f) reaction the influence of separate sets of P_n on the final results is about 3% for all combinations of CY and P_n. Therefore, most likely the difference in ν_d obtained with CY data from different libraries is due to discrepancies in the CY databases. Data combination of CY from JEFF and P_n set from (P-K-M) gives the closest to the recommended value (0.65 neutr./100 fiss.). Other sets of P_n give for the JEFF database the ν_d values which are in the range 0.64-0.66 neutr./100 fiss.

For the ^{239}Pu(n_{fast},f) reaction all combinations of the P_n sets with the CY data from ENDF/B and ROSFOND give the ν_d values which agree with the recommended values (0.651 neutr./100 fiss.). The ν_d data obtained on the basis of the fission product yields from JEFF strongly differ from the recommended one (0.71-0.73 neutr./100 fiss.). Thus the most consistent databases of CY for the ^{239}Pu(n_{th},f) and ^{239}Pu(n_{fast},f) reactions are from the JEFF and ENDF/B libraries respectively.

3. Verification of the databases of the fission product yields on the basis of the average half-life of DN precursors.

The average half-life of the DN precursors was calculated with the help of following expression $<T_{1/2}> = \sum_i Pn_i \cdot CY_i \cdot T^i_{1/2} / \sum_i Pn_i \cdot CY_i$, where CY_i – the cumulative yield of i-th precursor, P_{ni} and $T^i_{1/2}$ – the DN emission probability and the half-life of i-th precursor, respectively. Summation was made over all precursors included in the appropriate data set.

The average half-life of the DN precursors for the experimental data on the relative abundances and half-lives was obtained using the following formula $<T_{1/2}> = \sum_i a_i \cdot T_i / \sum_i a_i$, where a_i and T_i – the relative abundances and the half-life of i-th DN group, respectively. Summation was made over 6 or 8 groups of delayed neutrons.

The average half-life of the DN precursors from the neutron induced fission of ^{235}U, ^{238}U and ^{239}Pu are presented in Tables 7-11 together with the recommended data [14], the summation calculations on the basis of the ENDF/B-VI library [8] and the most recent experimental work [15]. These data are plotted in the Figures 3-4. The recommendation on the average half-lives have been made by Subgroup 6 of the OECD NEANSC Working Party on International Evaluation Cooperation in 2002.

Table 7. The average half-life of the DN precursors from the thermal neutron induced fission of ^{235}U.

Set (P_n,$T_{1/2}$)	$<T_{1/2}>$, s					Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	Wahl [5]	ROSFOND-2010	[14] Recommended data	[15] Experimental data	[8] ENDF/B-VI (P_n,$T_{1/2}$)–E-W
E-W	7.17	7.16	9.01	8.67	9.01			8.14±0.02

P-K-M	6.99	6.97	8.92	8.57	8.92	9.02±0.34	8.98±0.11	-
Rudstam	7.48	7.46	9.19	8.85	9.19			-
IAEA	7.30±0.42	7.27±0.41	9.16±0.60	8.83	9.16±0.60			-

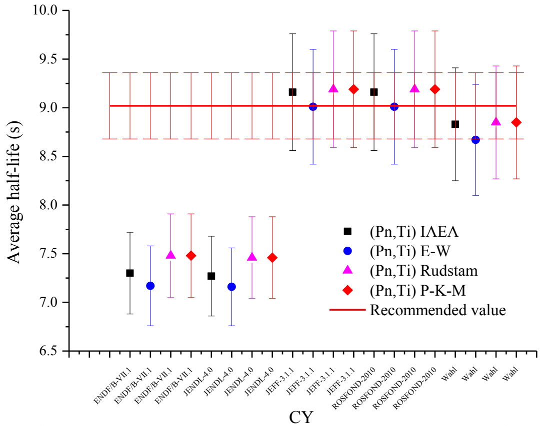

FIG. 3. The average half-life of the DN precursors related to the specific CY data base for all (P_n,$T_{1/2}$) sets from the thermal neutron induced fission of ^{235}U.

Table 8. The average half-life of the DN precursors from the fast neutron induced fission of ^{235}U.

Set (P_n,$T_{1/2}$)	<$T_{1/2}$>, s				Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	ROSFOND-2010	[14] Recommended data	[15] Experimental data	[8] ENDF/B-VI (P_n,$T_{1/2}$)-E-W
E-W	7.4	7.32	8.15	8.15	9.03±0.08 (0.59 MeV)	8.83±0.25	7.54±0.02
P-K-M	7.27	6.88	8.12	8.12			-
Rudstam	7.6	7.54	8.31	8.31			-
IAEA	7.42±0.56	7.35±0.55	8.29±0.54	8.29±0.54			-

Table 9. The average half-life of the DN precursors from the fast neutron induced fission of ^{238}U.

Set (P_n,$T_{1/2}$)	<$T_{1/2}$>, s					Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	Wahl [5]	ROSFOND-2010	[14] Recommended data	[15] Experimental data	[8] ENDF/B-VI (P_n,$T_{1/2}$)-E-W
E-W	4.87	4.87	5.01	4.74	4.87	5.32±0.14	5.32±0.05	5.05±0.01
P-K-M	4.69	4.70	4.84	4.58	4.68			-
Rudstam	5.12	5.13	5.30	5.07	5.12			-
IAEA	4.99±0.42	5.00±0.42	5.14±0.21	4.87	4.99±0.42			-

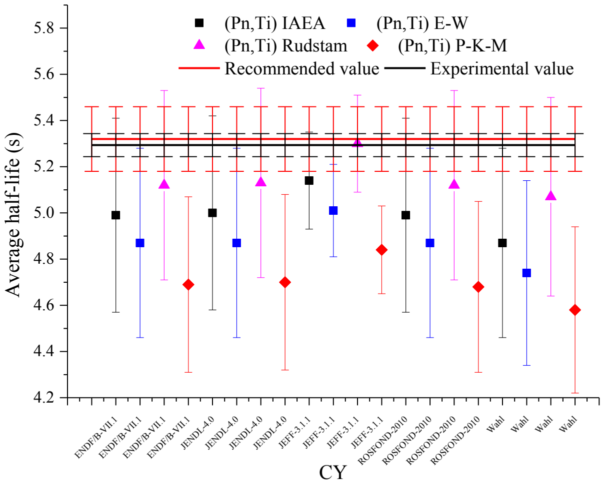

FIG. 4. The average half-life of the DN precursors related to the specific CY data base for all $(P_n,T_{1/2})$ sets from the fast neutron induced fission of ^{238}U.

Table 10. The average half-life of the DN precursors from the thermal neutron induced fission of ^{239}Pu.

Set $(P_n,T_{1/2})$	$<T_{1/2}>$, s					Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	Wahl [5]	ROSFOND-2010	[14] Recommended data	[15] Experimental data	[8] ENDF/B-VI $(P_n,T_{1/2})$-E-W
E-W	9.76	9.51	10.19	10.17	9.76	10.69±1.11	10.59±0.17	9.88±0.02
P-K-M	9.58	9.36	10.19	10.05	9.58			-
Rudstam	10.01	9.80	10.62	10.47	10.01			-
IAEA	9.81±0.51	9.59±0.57	10.43±1.20	10.31	9.81±0.51			-

Table 11. The average half-life of the DN precursors from the fast neutron induced fission of ^{239}Pu.

Set $(P_n,T_{1/2})$	$<T_{1/2}>$, s				Data from literature		
	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1.1	ROSFOND-2010	[14] Recommended data	[15] Experimental data	[8] ENDF/B-VI (Pn,T1/2)-E-W
E-W	10	9.74	8.81	10	10.09±1.26	10.27±0.13 (E_n=0.86 MeV)	10.12±0.02
P-K-M	9.91	9.68	8.85	9.90			-
Rudstam	10.28	10.05	9.14	10.25			-
IAEA	10.14±1.25	9.90±1.23	9.02±1.02	10.13±1.25			-

The data presented in Tables 7-11 allow the sensitivity of the $<T_{1/2}>$ value to individual $(P_n,T_{1/2})$ sets to be estimated using the minimum and maximum $<T_{1/2}>$ value obtained for the CY database of the considered fission reactions presented in a separate library for all sets of the $(P_n,T_{1/2})$ data sets – $d<T_{1/2}(P_n,T_{1/2})>/<T_{1/2}>=(max<T_{1/2}> - min<T_{1/2}>)/<T_{1/2}>min$. The obtained results are presented in Table 12.

Table 12. The sensitivity of the $<T_{1/2}>$ values to the individual $(P_n,T_{1/2})$ data sets.

CY database	$d<T_{1/2}(P_n)>/<T_{1/2}> = (<T_{1/2}>max-<T_{1/2}>min)/<T_{1/2}>min$, %				
	^{235}U(n_{th},f)	^{235}U(n_f,f)	^{238}U(n_f,f)	^{239}Pu(n_{th},f)	^{239}Pu(n_f,f)
ENDF/B-VII.1	7.0	4.5	9.2	4.5	3.7
JENDL-4.0	7.0	9.6	9.1	4.7	3.2
JEFF-3.1.1	2.6	2.3	9.5	4.2	3.3
Wahl	3.3	-	10.7	4.5	-
ROSFOND-2010	2.6	2.3	9.2	4.5	3.5

The analysis of the data presented in Table 12 shows that influence of separate sets $(P_n,T_{1/2})$ on the $<T_{1/2}>$ value is almost identical for all CY sets of the considered fission reactions except the CY data from ENDF/B and JENDL libraries for the case of the thermal and fast neutron induced fission of ^{235}U. It should be noted also the high sensitivity of the $<T_{1/2}>$ value to the individual set $(P_n,T_{1/2})$ in case of the fast neutron induced fission of ^{238}U for all considered CY sets. Below we will carry out the analysis of the results obtained for each of the considered fission reactions.

3.1. Reaction ^{235}U(*n,f*)

The discrepancies of the $<T_{1/2}>$ values obtained with the CY databases from the considered libraries reach up to 22% for the thermal neutron induced fission of ^{235}U (^{235}U(n_{th},*f*)). Low sensitivity of the $<T_{1/2}>$ values to the $(P_n,T_{1/2})$ sets for ^{235}U(n_{th},*f*) indicates that these discrepancies are mainly due to the fission product yields data. The CY database from the JEFF and ROSFOND libraries give the closest to the recommended $<T_{1/2}>$ value

(9.02±0.34 s) for all sets (P_n,$T_{1/2}$) – (8.92-9.19 s). The best agreement with the recommended data is observed for the (P_n,$T_{1/2}$) sets from E-W [8] and P-K-M [6]. The CY database from the ENDF/B and JENDL libraries give underestimated <$T_{1/2}$> values in the range (6.99-7.48 s) depending on the used (P_n,$T_{1/2}$) set. The low <$T_{1/2}$> value indicates a strong distortion of the time dependence of the DN decay curves caused by the underestimation of the contribution of DN precursors with large $T_{1/2}$ or overestimation of the contribution of the short-living DN precursors. Thus the fission product yields CY for the ^{235}U(n_{th},f) reaction presented in the JEFF, ROSFOND libraries and Wahl data [5] are the most correct from the standpoint of the reproduction of the time dependence of DN activity.

As for the ^{235}U(n_{fast},f) reaction the cumulative yields CY from the JEFF and ROSFOND libraries give the <$T_{1/2}$> value (8.31±0.54 s) that is 6% lower than the appropriate recommended <$T_{1/2}$> data (9.03±0.08 s). This value of <$T_{1/2}$> indicates most probably an overestimation of a contribution of short living DN precursors in an integral DN decay curve. The greater discrepancy with experimental data is observed for the fission yields CY from the JENDL and ENDF/B libraries – 14%. Therefore, it is possible to consider the CY sets from the JEFF and ROSFOND library as the preferable ones.

3.2. Reaction ^{238}U(n,f)

As in the case of the ν_d data from the ^{238}U(n,f) reaction the <$T_{1/2}$> value is also the most sensitive to individual (P_n,$T_{1/2}$) set as compared with other nuclear reactions showing thereby that another groups of the DN precursors play significant role in forming the time dependence of DN activity. As a rule the P_n and $T_{1/2}$ data for these precursors were obtained with the help of calculations on the basis of different model and systematics that results in large uncertainties of these data as well as discrepancies of these data in different (P_n,$T_{1/2}$) sets. Most probably the observed <$T_{1/2}$> data spread is due to individual properties of each (P_n,$T_{1/2}$) set that is confirmed by a similar dependence of the <$T_{1/2}$> value on (P_n,$T_{1/2}$) set for all CY sets. A variation of the average <$T_{1/2}$> value observed for the considered CY database sets can be explained by the possible shift of the most probable charge in isobaric chains of the independent fission yields. As it can be seen from Table 9 and FIG.4 the time dependence of DN activity obtained with the fission product yields from the JEFF library and the (P_n,$T_{1/2}$) set from the Rudstam database better reproduces the recommended data as compared with other combination of CY and (P_n,$T_{1/2}$).

3.3. Reaction ^{239}Pu(n,f)

For the thermal neutron induced fission of ^{239}Pu the closest to the experimental data <$T_{1/2}$> give the cumulative yields CY from the JEFF library and Wahl's data set [5] when using sets (P_n,$T_{1/2}$) from [7] and IAEA [9]. The <$T_{1/2}$> data obtained using the CY yields from the ENDF/B, JENDL and ROSFOND libraries differ from the experimental one by 6-7%.

In the case of the fast neutron induced fission of ^{239}Pu the closest to experimental <$T_{1/2}$> data were obtained for the fission product yields from the ROSFOND and ENDF/B libraries: 10.14±1.25 s with the (P_n,$T_{1/2}$) set from IAEA [9] and 10.28±1.27 s with the set from [7]. The <$T_{1/2}$> values obtained using the fission yields from the JEFF library differ from experimental one by 10%. On the basis of the obtained results it is possible to consider that the most correct data on the fission product yields from the standpoint of the time dependence of DN activity for the ^{239}Pu(n_{th},f) reaction are those presented in the JEFF library, and for the ^{239}Pu(n_{fast},f) reaction– in the ENDF/B and ROSFOND libraries.

4. Conclusion

In the present work, the summation method is used for the determination of the most reliable data sets of the fission product yields, which are presented in the latest version of the ENDF/B, JEFF, JENDL, ROSFOND libraries. The criterion for a choice was the consistency of the calculated macroscopic (aggregate) characteristics of delayed neutrons (ν_d and $<T_{1/2}>$) with the corresponding evaluated experimental data.

It was found that the sensitivity of the ν_d and $<T_{1/2}>$ data to the individual sets of the (P_n,$T_{1/2}$) data used in calculation depends on the fissioning system. In the considered reactions there were low (1.1-1.2%), middle (2.7-3.1%) and high (7.9-9.9%) value of the sensitivity in case of ^{235}U(n,f), ^{239}Pu(n,f) and ^{238}U(n,f) reactions, respectively. It was proposed that the high sensitivity to the (P_n,$T_{1/2}$) data for ^{238}U(n,f) was connected with appearance of another group of DN precursors with significant yields as compared with ^{235}U(n,f) and ^{239}Pu(n,f) reactions. This group consists of mainly short-lived DN precursors because the average half-life for ^{238}U is essentially less than for ^{235}U and ^{239}Pu (5.3 s against 9.03 and 10.09 s). As a rule the P_n and $T_{1/2}^i$ data for these precursors were obtained with the help of calculations on the basis of different model and systematics that results in large uncertainties of these data as well as discrepancies of these data in different (P_n,$T_{1/2}$) sets.

Table 13 shows the couples of data CY-(P_n,$T_{1/2}$) which give the closest to the recommended values of the total delayed neutrons yield.

Table 13. The most consistent microscopic data sets for the determination of ν_d.

Input data	Origin of the CY and (P_n,$T_{1/2}$) data sets				
	^{235}U(n_{th},f)	^{235}U(n_f,f)	^{238}U(n_f,f)	^{239}Pu(n_{th},f)	^{239}Pu(n_f,f)
CY	JEFF-3.1.1	ENDF/B-VII.1	JEFF-3.1.1	JEFF-3.1.1	ENDF/B-VII.1
(P_n,$T_{1/2}$)	All sets	Rudstam [7]	P-K-M [6]	All sets	All sets

Table 14 shows the couples of data CY-(P_n,$T_{1/2}$) which give the closest to the recommended values of the average half-life of their precursors.

Table 14. The most consistent microscopic data sets for the determination of $<T_{1/2}>$.

Input data	Origin of the CY and (P_n,$T_{1/2}$) data sets				
	^{235}U(n_{th},f)	^{235}U(n_f,f)	^{238}U(n_f,f)	^{239}Pu(n_{th},f)	^{239}Pu(n_f,f)
CY	JEFF-3.1.1	JEFF-3.1.1	JEFF-3.1.1	JEFF-3.1.1	ENDF/B-VII.1
(P_n,$T_{1/2}$)	All sets	IAEA [9], Rudstam [7]	Rudstam [7]	IAEA [9], Rudstam [7]	IAEA [9], E-W [8], Rudstam [7]

It turns out that the CY database that is the most consistent with the macroscopic DN data (ν_d and $<T_{1/2}>$) in the considered reactions are included in the JEFF-3.1.1 library except the fission product yields from the ^{239}Pu(n_f,f) reaction. In this last case, the most appropriate CY data is presented in the ENDF/B-VII.1 library.

It is seen also from the Table 13 that the most reliable (P_n,$T_{1/2}$) data is presented in the IAEA microscopic data set [9]. Low sensitivity of the ν_d data and its good agreement for all CY data sets in case of the ^{235}U(n_f,f) reaction indicates a more pronounce energy dependence of ν_d then that presented in the last recommendation [11].

On the one hand obtained results shows effectiveness of the proposed approach in choosing the most reliable data on the fission product yields. On the other hand, a comparative analysis of the data revealed a number of issues, whose solution, will undoubtedly help to create new approaches designed to validate the database for the fission product yields.

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