The JEF-2.2 Nuclear Data Library
JEF 2-2

JEF/DOC - 731

Preliminary evaluation of the LENDEL et al model to calculate the delayed neutron yield as a function of energy. First results of the JEF2.2 data validation.

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I. INTRODUCTORY COMMENTS

In order to calculate the delayed neutron yield as a function at energy, the first question that one can pose is :

What is the relevance of the energy dependence of delayed neutrons yields ?

At the time t after scission, the average number of delayed neutron is :

$$\overline{n_d}(t) = \sum_i \lambda_i P_{n_i} \; Y_i \; e^{-\lambda_i t}$$

In this expression i stands for the precursor which is produced with a yield Y_i and which decays with a time constant λ_i. P_{n_i} refers to the probability of neutron emission by the emitter.

Consequently the total average delayed neutron yield is obtained by :

$$\overline{\nu_d} = \int_0^\infty \overline{n_d}(t)dt$$

Therefore, for a given fissioning nucleus $\overline{\nu_{d_i}}$ is a function of P_{n_i} and Y_i. Obviously the P_{n_i} are not affected by the variation of the incident energy, but should the same be for the Y_i ?

The probability of neutron emission is clearly influenced by the neutron separation energy of the emitter, so that most emitters are located in the fission product (FP) mass region in the vicinity of neutron closed shells.
The FP mass distribution varies with the incident energy, and in particular, in the region of the delayed neutron emitters. From this qualitative point of view the question of the energy dependence of the ν_d is relevant. It should be noted that the FP which are delayed neutron emitters correspond to fragments which are poor emitters of prompt neutrons. In other words, the competition between prompt and delayed neutron emission is only partial, and for the same reasons as above, it is also energy dependent.

The question of the energy dependence of the delayed neutron yield has already been discussed in previous publications by numerous authors, relative to both the absolute yield, namely by Masters, Thorpe and Smith [9], Krick and Evans [2], Evans, Thorpe and Krick [3], Alexander and Krick [4], and the consequences for the value of beta effective by D'Angelo and Filip [6].
From these publications several features, all energy dependent, can be noted for the delayed neutron yield :

the odd-even effect which decreases with the incident energy, but reappears at the occasion of the competition with the second and third chance fission processes involving additional fissioning systems at lower excitation energies.

This has been pointed out by Alexander and Krick [4] among others.

- the Zp model -the most probable charge parameter for the same isobars- as indicated by Nethaway [5], which governs the fraction between independent and cumulative yields.
- the competition with prompt neutrons emission.

The important questions that now arise are :

- **Is this energy dependence of importance for the calculation of reactor parameters ?**

One of the main tasks of WPEC subgroup 6 is to provide a substantial answer to this question.

- **Is there any reliable model to calculate $\nu_d(E)$?**

Several attempts have been made in the past to propose formalisms, which were very simple and resulted from the observation of systematic trends. Obviously they were not satisfactory.

In 1962 Moscati and Goldenberg noted that the delayed neutron yield at thermal energies is a negative exponential function of the parameter ($3Z_f$ - A_f), Z_f and A_f being the charge and the mass of the fissioning nucleus.

This behaviour has been confirmed by Paï [7], and by Waldo and co-workers [8] who determined the formula for the delayed neutron yield (for 100 fissions) :

$$Y_d(100\ \text{fissions}) = Y_0\, e^{-K(3.03Z_f - A_f)}$$

Tuttle [9] modified this parametrisation by considering the parameter $(3Z_f - A_f)\cdot\frac{A_f}{Z_f}$.

In order to calculate the cumulative and independent fission yields the most probable charge Z_p for a given mass chain must be known. It appears that the first attempt to take into account the effect of an incident energy variation was via a parametrization of Z_p as a function of $\nu_p(E)$ [10].

Wahl and Co-workers determined the following relationship :

$$Z_p(A,E,A_c) = 92\cdot\frac{\left[A + \nu_p(A,E)\right]}{A_c}$$

where A is the mass number of the fragment, A_c is the mass number of the fissioning system and $\nu_p(A,E)$ is the number of prompt neutrons emitted by the fragment.

The other important effect, also energy dependent, is the odd-even effect.

Alexander and Krick [4] approximately determined this effect and explained the rapid drop observed experimentally in the delayed neutron yield in the region of the second chance fission threshold. In this energy two fissioning systems are present : the system (A+1), and the system of mass A whose relative ›ution to total fission rapidly increases with the incident energy. Compared to the system (A+1) the system A is at a lower excitation energy where the odd-even effect is assumed to be higher with the consequence of a lower delayed neutron yield. In fact a higher odd-even effect results in a lower delayed neutron yield for odd Z precursors and in a higher delayed neutron yield for even Z precursors. As the precursors are of mostly odd Z the total delayed neutron yield is reduced. However this effect is in competition with the $Z_p(E)$ effect which maybe explains why the gradient of $\nu_d(E)$ in the single chance fission range is rather low.

II A NEW FORMALISM TO CALCULATE ν_d(E) BY LENDEL AND CO-WORKERS [11]

All of the physical phenomena mentioned above were not registered in a formalism, and the calculation of ν_d was performed either by using rough empirical formulas or by the summation technique. The summation technique, which is a preferential way of understanding the physical problems presented here, is time consuming and inaccurate. Hence, a basic improvement was required.

This situation changed with the definition of a semi empirical formula by Lendel and co-workers [11] (LM). who integrated previous findings with additional refinements.

Firstly, new systematics are proposed for the most probable charge Z_p including corrections for pairing and shell effects, making a distinction between light and heavy FP :

$$Z_p = \frac{Z_f}{2} + 0.71\left[N + \frac{\nu_p(E)}{2} - \frac{N_f}{2}\right] + a\left\{5.98\frac{N_f}{Z_f} - 1.1e^{-\left(N+\frac{\nu_p(E)}{2}-b\right)^2/3.64} - 7.443\right\}$$

where N_f and Z_f are respectively the neutron and proton numbers of the fissioning nucleus.

$a = 1$	$b = 59.4$	$N \le \frac{N_f - \nu_p(E)}{2}$	→ light precursor
$a = -1$	$b = N_f - 59.4$	$N \ge \frac{N_f - \nu_p(E)}{2}$	→ heavy precursor

This relationship also expresses a redistribution of the protons in favour of the light fragment $\left((Z/N)_{light} > (Z/N)_{heavy}\right)$ which is now a well accepted feature of the fission process.

Finally, the absolute total yield of delayed neutrons (per 100 fissions) is given as :

$$\nu_d(E) = Y_l(E) + \varphi(A_f, Z_f).\Psi(E)$$

where $Y_l(E)$ is the direct macroscopic yield, given by an expression very similar to that given by Paï which includes a term to describe the competition with prompt neutron emission :

$$Y_l(E) = e^{a_0 - b_0\, w(E)}$$

$$w(E) = \left[0.1904(2.626\, Z_f - A_f + \nu_p(E))\right]^2 + 0.1125\,(Z_f - 90)$$

$$a_0 = 2.43 \pm 0.13 \qquad b_0 = 0.725 \pm 0.026$$

The second part of the right hand side term should be considered as a correction to the macroscopic yield, and consists of two contributions :

$$\varphi(A_f, Z_f) = \frac{1}{3}\left[2.626\, Z_f - A_f + 0{,}375\,(Z_f - 92) - 2.59\right] \cdot \frac{Y_l(8\ \mathrm{MeV})}{Y_l(8\ \mathrm{MeV}, {}^{236}\mathrm{U})}$$

which is normalized to the experimental value of ν_d for the ^{236}U fissioning nucleus at an excitation energy of 8 MeV.

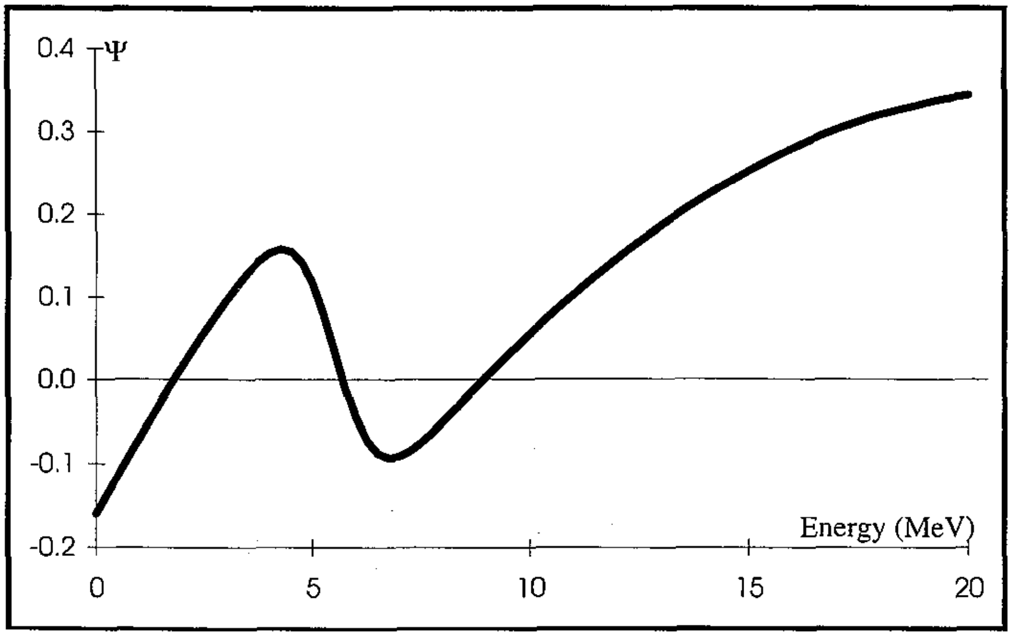
The second contribution is a polynomial function of the incident energy (see Figure 1).

$$\Psi(E) = -a_1 + a_2 \cdot E - a_3 \cdot E^2 - a_4 \cdot \mathrm{th}\,(E - 5.5)$$

where $a_1 = 0.41 \pm 0.05$ $\qquad a_2 = (9.68 \pm 0.15).10^{-2}$

$a_3 = (2.13 \pm 0.66).10^{-3}$ $\qquad a_4 = 0.25 \pm 0.044$

Figure 1

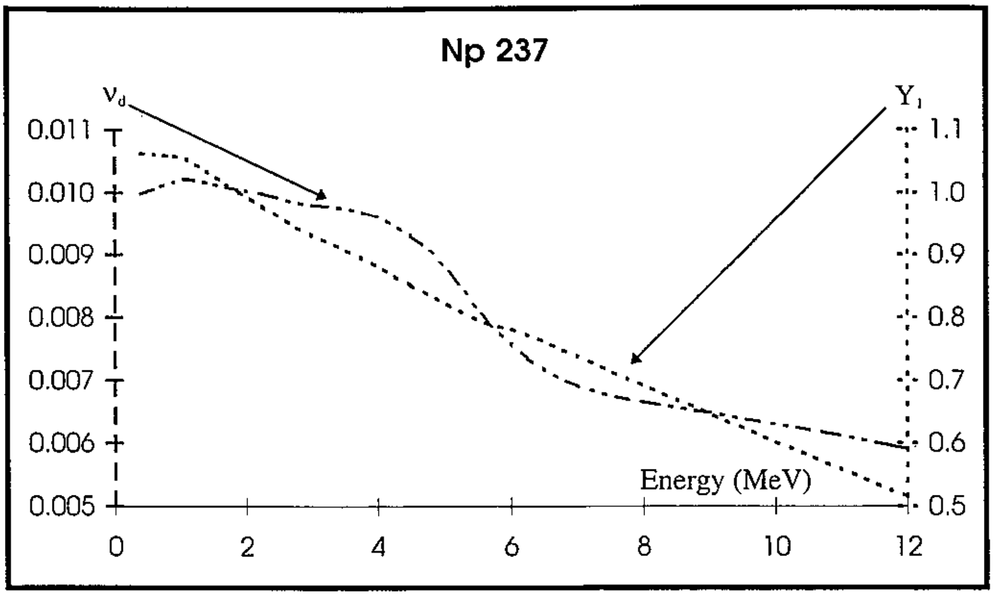


The role of the corrective term is to simulate the energy dependence of the odd-even effect in the first chance fissioning system together with the contribution from the cumulative yields. This representation could probably be improved as :

- $\Psi(E)$ does not represent the competition of the third chance fission,
- $\Psi(E)$ is identical for all the actinides, which is an approximation as the differences in fission barrier heights according to the isotopic family [12] are ignored.

Figure 2 shows the results obtained for ^{237}Np comparing the yield Y_1 to the final corrected value.

Figure 2



Given the above considerations the following improvements are proposed.

The competition between the 1st, 2nd and 3rd chance fissions could be better expressed by :

- considering the 3 fissioning nuclei involved,
- defining a new Ψ(E) function which is valid for a single fissionning nucleus. Consequently this function should express the odd-even effect combined to the cumulative yield contribution for this single nucleus, so as to obtain, in particular for odd nuclei, an effect limited to the contribution of this cumulative yields. At the moment this is not the case and the present Lendel formula should be considered, taking into account the restrictions mentioned above, to be valid only for the even Z nuclei in an energy range corresponding to the first chance fission.

In the context of the suggested improvements the total delayed neutron yield would have the following expression :

$$\nu_d(E) = \alpha_1(E)\,\nu_d^{A+1}(E) + \alpha_2(E)\nu_d^{A}(E) + \alpha_3(E)\nu_d^{A-1}(E) + \ldots$$

$$\sigma_{n,f} = \sigma_{n,f}^{A+1} + \sigma_{n,n'f}^{A} + \sigma_{n,2nf}^{A-1} + \ldots$$

$$\alpha_1(E) = \frac{\sigma_{n,f}^{A+1}}{\sigma_{n,f}} \qquad \alpha_2(E) = \frac{\sigma_{n,n'f}^{A}}{\sigma_{n,f}} \qquad \alpha_3(E) = \frac{\sigma_{n,2nf}^{A-1}}{\sigma_{n,f}}$$

The upperscripts refer to the fissionning nuclei, while the α_i coefficients represent the fraction of the i^{th} fission chance in the total fissioning process.

In this scheme a complete consistency is needed at each step of the calculation : at each energy above the second chance fission a consistency has to be reached for $\sigma_f(E)$, $\nu_p(E)$ and $\nu_d(E)$. This constraint can be helpful in order to infer information on one class of data ($\nu_d(E)$ for example) when clear information is already available for the two other classes.

'ery often it appears that some nuclei have not been measured or are radioactive with short half lifes (^{237}Pu, ...). For these nuclei, the revised evaluation is relevant for the modelling calculations of both the cross ıs and the prompt neutron yields.

To perform these modelling calculations all of the tools and relevant information are available :

- Concerning the calculation of σ_f :

The systematic trend for the parametrisation of the deformed optical model [13] (for coupled channel calculations) is used in conjunction with the statistical model (α, Sγ, ...) or the fission model (barrier parameters, fission channel density). It is shown in [12] that this is not a significant problem and it will not be discussed any further in this paper.

- Concerning the calculation of ν_p :

The phenomenological systematics which were in use 20 years ago should be avoided since numerous models now exist, all of which are based on the basic energy balance :

$$\overline{Q} + B_n + E = \overline{TKE} + \overline{E}_f^*$$

where $\overline{Q}$ stands for the energy release per fission,
B_n stands for the neutron binding energy in the fissioning nucleus,
$\overline{TKE}$ stands for the average total kinetic energy of the fragments before neutron emission,
$\overline{E}_f^*$ stands for the average total excitation energy of the fragments.

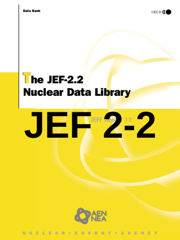
In this equation the average number of prompt neutrons is derived by splitting $\overline{E}_f^*$ into a term related to the neutron emission and a term related to the prompt γ emission.

$$\nu_p(E) = \frac{\overline{Q} + B_n + E - (\overline{TKE} + \overline{E}_\gamma^f)}{\overline{B}_n^f + \frac{4}{3}\left[\left(\overline{Q} + B_n + E - \overline{TKE}\right)/a\right]^{1/2}}$$

where $\overline{B}_n^f$ is the average neutron binding energy of the fragments,
$\overline{E}_\gamma^f$ is the average total prompt gamma energy emitted per fission,
a is the level density parameter for the fissioning nucleus.

All of the barred quantities are calculated by appropriate models and their reliability depends on how well the fragment distributions are predicted by each model.

Several models exist based on different approaches, and reviews of them are given in [14] and [15]. Among these quantities some are accessible only by model $\left(\overline{Q}, \overline{B}_n^f\right)$, and some of the others can either be measured or derived from well established systematics (Viola and Unik for $\overline{TKE}$, Hoffman for $\overline{E}_\gamma^f$).



Data has been calculated in this way for the $\nu_d(E)$ of ^{239}Pu, ^{235}U, ^{238}U and ^{237}Np, and the data for the two nuclei has been introduced in JEF2. Figures 3, 4 and 5 compare this data with ENDF/B-VI and JEF2 (^{238}U) together with the final microscopic data determined by Alexander and Krick.

Figure 3

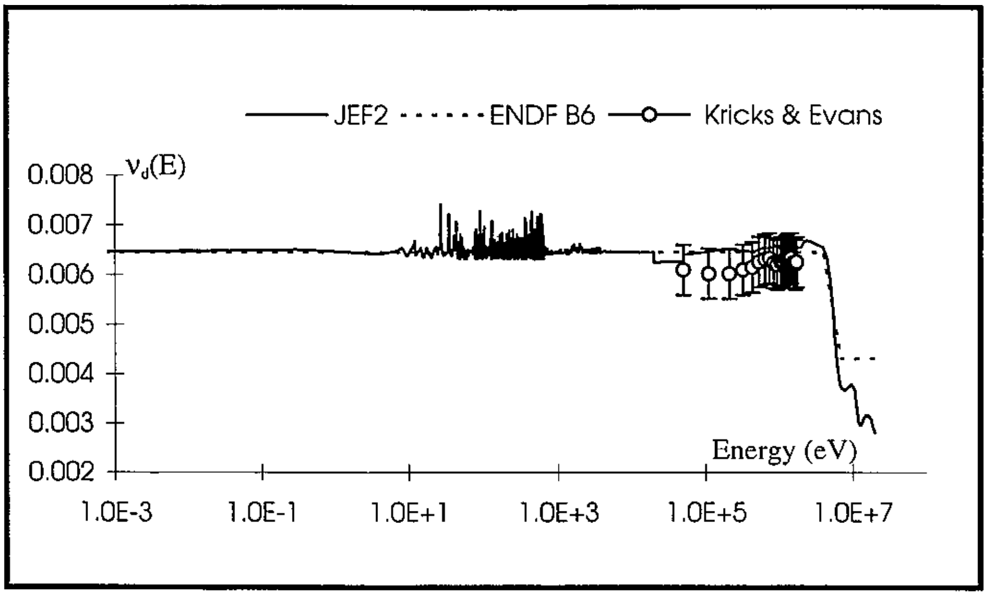
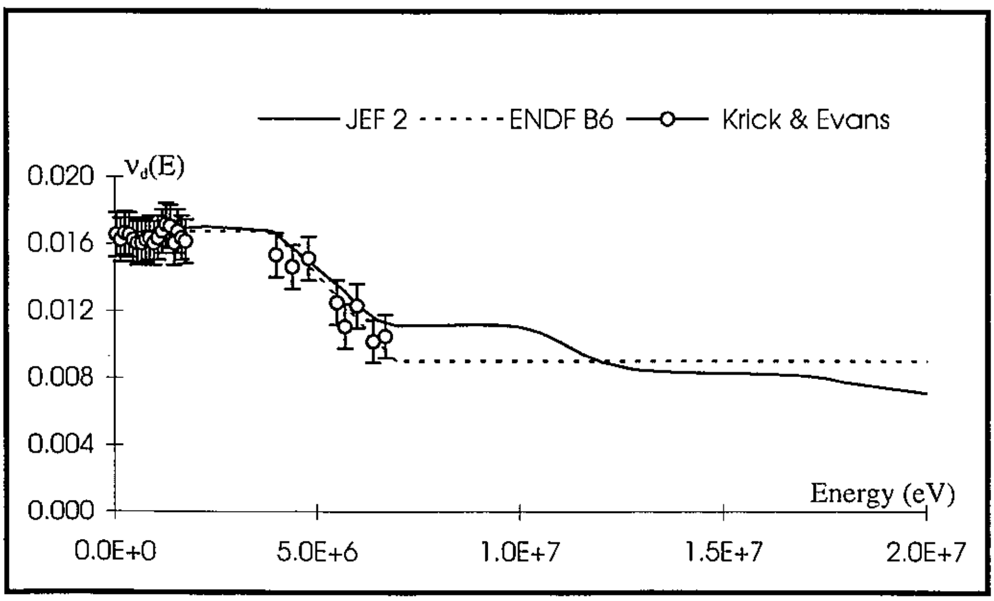


Figure 4



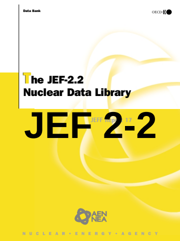


Figure 5

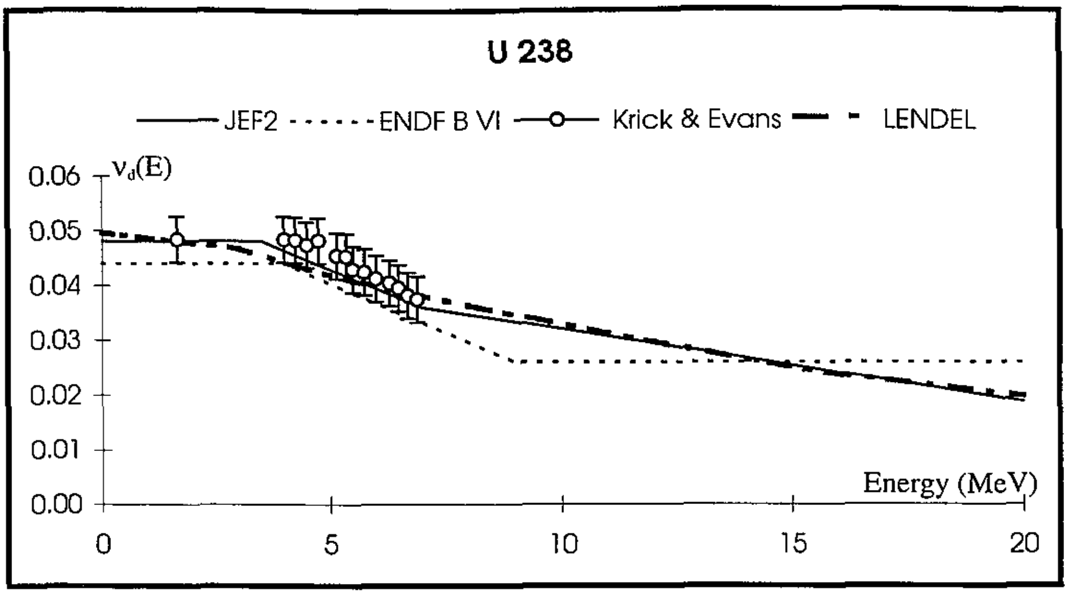
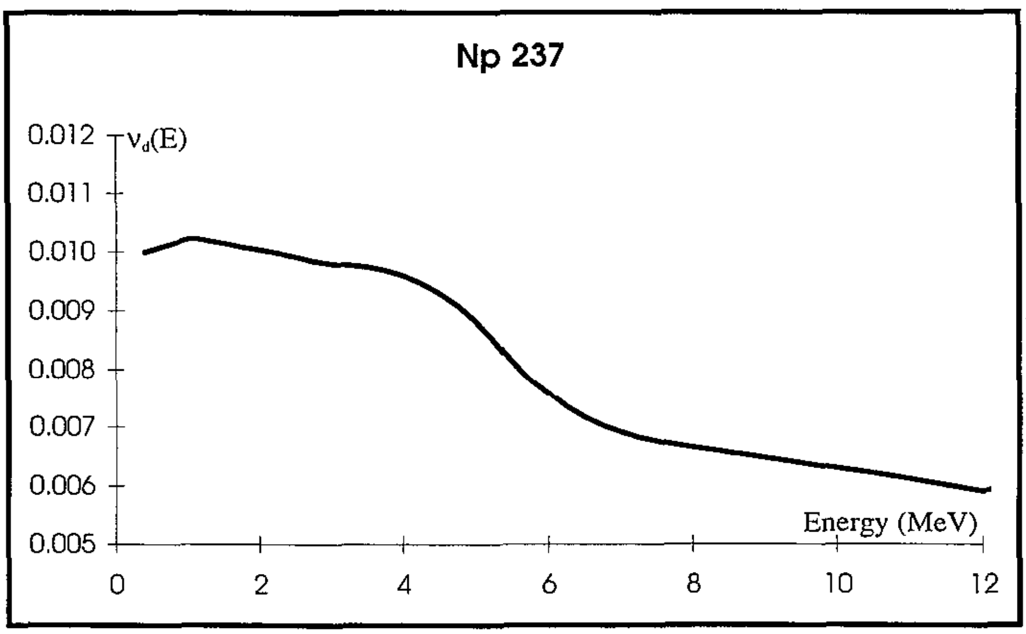


Figure 6



One observes that the slope for the LM ν_d(E) data is positive for ^{235}U and ^{239}Pu while it is negative for ^{238}U. There is a good agreement between the model and the experimental data, but the experimental uncertainties are such that one can hardly find a justification for a slope in the first chance fission range. At this stage of the intercomparison it should be emphasised that the LM has been based essentially on data for Th and U isotopes and is maybe not fully adequate for the other isotopic families.

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NTEREST OF INTEGRAL INFORMATION

The experimental information on ν_d obtained directly at the aggregate level, or at the individual (precursors) level, is scarce and the related uncertainty is not adequate when compared to the requested uncertainty in order to predict the fission reactor reactivity scale.

As pointed out by Filip and D'Angelo in [16] and [6] the β_{eff} data obtained in clean cores provides a valuable source for improvement. A formalism derived from that of Keepin has been elaborated by Filip [17] by introducing an explicit energy dependence for ν_d It is shown that when applied to clean cores the formalism leads to a quasi separation of the space energy distributions, as well as the ν_d and χ_d effects for β_{eff}. This induces significant simplifications since the β_{eff} value related to the full core can be reduced with small modifications to a value at the center of the core (such values are marked with an upperscript (0)) where there is a fundamental mode flux). This simplification is also valid for sensitivity coefficients which are calculated from a fundamental mode flux.

The β_{eff} value depends on all of the parameters which contribute to the neutron flux at equilibrium (namely the fission neutron yield and the cross sections for the fission, absorption and diffusion processes) in addition to the delayed neutron yield ν_{di} for the i fissile isotopes.

The set of sensitive parameters for an integral experiment k is given by : $\{P_k\} = \{\nu_{d_i}, \nu_{t_i}, \Sigma_f^k, \Sigma_{abs}^k, \Sigma_{scat}^k\}$

This can be divised into two parts, one referring to ν_{di} only, and the second part containing all of the other parameters, so that the relative discrepancy between the experimental and the calculated value for $\beta_{eff,k}$ can be expressed as :

$$\left(\frac{E-C}{C}\right)^k = \sum_i {}^k S_{\nu_{d_i}}^{\beta_{eff}} \cdot \frac{\delta\nu_{d_i}}{\nu_{d_i}} + \sum_j {}^k S_{p_j \neq \nu_{d_i}}^{\beta_{eff}} \cdot \frac{\delta p_j}{p_j}$$

In the adjustment procedure to validate nuclear data and/or to produce an "adjusted" data library for a neutronic "formulaire" a choice is made between two approaches :

- either including β_{eff} data in the global set of integral data and adjusting all of the nuclear parameters in the same way ;
- or proceeding in two steps : first by adjusting all of the parameters with relevance to the neutron flux (cross sections, ν_p, ...), and then secondly adjusting $\nu_{d,i}$ for β_{eff} data which are only calculated using the adjusted data from the first step.

This last procedure has the following advantages :

- to focus on the privileged dependence of β_{eff} on the $\nu_{d,i}$;
- to "decouple" the "direct" effect from the other effects ;
- to justify the reglect of the sensitivities other than $S_{\nu_{d_i}}^{\beta_{eff}}$.

This approach has been chosen to analyse thirteen fast integral experiments performed on MASURCA, …K, ZPR and FCA facilities.

Neutronics calculations have been performed using the new formulaire ERANOS [13] and the adjusted cross-section data library ERALIB1 [18] in the 33 group ECCO energy scheme. The delayed neutron input data have been taken from JEF2.2 and ENDF/B-VI. When the Keepin formalism was used a constant value of ν_d was used in order to preserve the consistency with the energy dependent formalism, and obtained by weighting by the total fission rate in the following way :

$$\overline{\nu_{d_i}} = \frac{\int \nu_{d_i}(E) \cdot \sigma_{f_i}(E) \cdot \phi(E) dE}{\int \sigma_{f_i}(E) \cdot \phi(E) dE}$$

* Direct calculation results :

For a same set of delayed neutron input data it is interesting to note that the calculated β_{eff} values are consistent if one uses the two formalisms, as is shown in Table 1. This is important since it has been carefully verified that both formalisms and their related algorithms give identical results (to within less than 3 pcm in terms of reactivity) when consistent ν_d data are introduced as input data. By consistent data we mean the real energy dependent $\nu_d(E)$ when used by the improved formalism on one side, and a constant value obtained by weighting $\nu_d(E)$ by the fission rate (in the fundamental mode of the mock-up under consideration) when used by the Keepin formalism on the other side.

Table 1

Calculated and measured β_{eff} values (pcm)

JEF2

			U235	U238	Pu239	Pu240	Pu241	Pu242	Total	Exp. Unc. %	(E-C)/C %
A	R2	Exp.							719	2,4	
		Keepin	565,0	176,3	0,0				741,2		-3,00
		Mod.K..	564,9	176,3	0,0				741,2		-3,00
	ZONA2	Exp.							345	2,3	
		Keepin	8,2	170,3	146,6	12,9	9,9	0,7	348,6		-1,04
		Mod.K.	8,2	170,4	146,6	12,9	9,9	0,7	348,7		-1,05
B	7A	Exp.							395	3,0	
		Keepin	31,7	197,2	149,9	5,1	4,0	0,0	387,8		1,85
		Mod.K.	31,7	196,9	149,8	5,1	4,0	0,0	387,5		1,94
	7B	Exp.							429	3,0	
		Keepin	49,7	256,8	124,3	3,7	3,2	0,0	437,8		-2,00
		Mod.K.	49,7	256,6	124,3	3,7	3,2	0,0	437,6		-1,98
	9C1	Exp.							748	3,2	
		Keepin	540,5	208,4	0,0				748,9		-0,11
		Mod.K.	540,5	207,9	0,0				748,4		-0,06

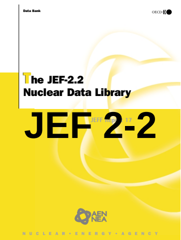

Table 1 (Continued)

Calculated and measured β_{eff} values (pcm)

Group	Case		U235	U238	Pu239	Pu240	Pu241	Pu242	Total	Exp. Unc. %	(E-C)/C %
	C2	Exp.							416	4,5	
		Keepin	50,4	197,7	143,4	5,0	2,9	0,0	399,5		4,13
		Mod.K.	50,4	197,4	143,4	5,0	2,9	0,0	399,1		4,23
	C Ref	Exp.							381	2,0	
		Keepin	7,0	225,8	136,1	6,0	5,7	0,1	380,8		0,05
		Mod.K.	7,0	225,9	136,1	6,0	5,7	0,1	380,8		0,04
C	Pu C SS	Exp.							222	2,0	
		Keepin	0,0		217,5	2,6	1,7	0,0	221,8		0,08
		Mod.K.	0,0		217,5	2,6	1,7	0,0	221,8		0,09
	RSR	Exp.							335	2,0	
		Keepin	4,8	148,0	164,4	6,6	4,6	0,1	328,6		1,96
		Mod.K.	4,8	148,1	164,3	6,6	4,6	0,1	328,6		1,95
C	U9	Exp.							706	2,0	
		Keepin	332,6	393,7					726,3		-2,79
		Mod.K.	332,2	393,3					725,5		-2,69
	U Fe	Exp.							667	2,0	
		Keepin	672,3	2,2					674,5		-1,11
		Mod.K.	672,2	2,2					674,4		-1,10
	U Fe Leak	Exp.							672	2,0	
		Keepin	672,3	2,1					674,4		-0,36
		Mod.K.	672,2	2,1					674,3		-0,34
D	X1X	Exp.							738	2,0	
		Keepin	726,8	39,9					766,7		-3,74
		Mod.K.	726,7	36,6					763,3		-3,31

ENDF/B-VI

Group	Case		U235	U238	Pu239	Pu240	Pu241	Pu242	Total	Exp. Unc. %	(E-C)/C %
	R2	Exp.							719	2,4	
		Keepin	567,1	161,8	0,0				728,9		-1,36
		Mod.K.	567,3	161,8	0,0				729,1		-1,39
A	ZONA2	Exp.							345	2,3	
		Keepin	8,2	156,3	148,2	13,1	10,1	0,7	336,6		2,49
		Mod.K.	8,2	156,3	148,2	13,1	10,4	0,7	337,0		2,36
	7A	Exp.							395	3,0	
		Keepin	31,8	197,0	150,5	5,2	4,0	0,0	388,5		1,67
		Mod.K.	31,7	196,9	149,8	5,1	4,0	0,0	387,5		1,94

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Table 1 (Continued)

Calculated and measured β_{eff} values (pcm)

Facility	Config.		U235	U238	Pu239	Pu240	Pu241	Pu242	Total	Exp. Unc. %	(E-C)/C %
	3	Exp.							429	3,0	
		Keepin	50,0	235,7	126,3	3,8	3,3	0,0	419,1		2,37
		Mod.K.	50,0	235,6	126,3	3,8	3,4	0,0	419,1		2,36
B	9C1	Exp.							748	3,2	
		Keepin	542,5	191,2	0,0				733,8		1,94
		Mod.K.	542,7	190,8	0,0				733,5		1,98
	9C2	Exp.							416	4,5	
		Keepin	50,6	181,5	144,0	5,1	3,0	0,0	384,1		8,30
		Mod.K.	50,6	181,1	144,1	5,1	3,1	0,0	384,0		8,34
	C Ref	Exp.							381	2,0	
		Keepin	7,1	207,3	138,8	6,2	5,8	0,1	365,3		4,30
		Mod.K.	7,1	207,3	138,8	6,2	6,0	0,1	365,5		4,24
	Pu C SS	Exp.							222	2,0	
		Keepin	0,0		216,0	2,6	1,7	0,0	220,2		0,81
		Mod.K.	0,0		216,0	2,6	1,7	0,0	220,3		0,78
	RSR	Exp.							335	2,0	
		Keepin	4,8	135,8	165,9	6,7	4,7	0,1	318,1		5,32
		Mod.K.	4,9	135,9	165,9	6,7	4,8	0,1	318,3		5,25
C	U9	Exp.							706	2,0	
		Keepin	334,1	361,4					695,5		1,50
		Mod.K.	333,6	361,0					694,7		1,63
	U Fe	Exp.							667	2,0	
		Keepin	676,1	2,1					678,2		-1,65
		Mod.K.	676,2	2,1					678,3		-1,66
	U Fe Leak	Exp.							672	2,0	
		Keepin	676,2	1,9					678,1		-0,90
		Mod.K.	676,3	1,9					678,2		-0,91
D	X1X	Exp.							738	2,0	
		Keepin	730,8	36,6					767,4		-3,83
		Mod.K.	731,4	36,6					767,9		-3,90

A : MASURCA B : SNEAK C : ZPR D: FCA

Exp : Experience

Keepin : Keepin formalism

Mod. K : Modified Keepin formalism

justment results :

The sensitivity coefficients have been calculated in the following way :

$$ {}^{k}S^{\beta_{eff}}_{\nu_{d_i}} = \frac{{}^{k}\beta_{eff}}{\beta_{eff}} = \frac{\tilde{\nu}_{d_i} \cdot \tilde{F}_i}{\sum_i \tilde{\nu}_{d_i} \cdot \tilde{F}_i} $$

(In this notation, which is that of reference [17], the ~ symbol represents the energy averaging with the neutron spectrum as a weighting function).

The resulting values corresponding to the Keepin and modified formalisms are given in Table 2 and 3 respectively. The adjustments have been performed using the statistical consistent method and so for the calculation of β_{eff} with the modified formalism an energy scheme of 5 groups has been considered whose boundaries are as follows :

Group number :		1		2		3		4		5	
Energy :	Thermal energy	--	10 KeV	--	2 MeV	--	4 MeV	--	7 MeV	--	20 MeV

(The consideration of the third chance fission has been omitted in the last energy group due to the absence of sufficient integral data.)

Table 2

Sensitivity coefficients using Keepin formalism (%)

JEF2

		U235	U238	Pu239	Pu240	Pu241	Pu242	Total
A	**R2**	76,2	23,8	0,0	0,0	0,0	0,0	100,0
A	**ZONA2**	2,3	48,8	42,1	3,7	2,8	0,2	100,0
B	**7A**	8,2	50,8	38,6	1,3	1,0	0,0	100,0
B	**7B**	11,4	58,7	28,4	0,9	0,7	0,0	100,0
B	**9C1**	72,2	27,8	0,0	0,0	0,0	0,0	100,0
B	**9C2**	12,6	49,5	35,9	1,3	0,7	0,0	100,0
	C Ref	1,8	59,3	35,7	1,6	1,5	0,0	100,0
	Pu C SS	0,0	0,0	98,1	1,2	0,7	0,0	100,0
	RSR	1,5	45,1	50,0	2,0	1,4	0,0	100,0

Table 2 (Continued)

Sensitivity coefficients using Keepin formalism (%)

		U235	U238	Pu239	Pu240	Pu241	Pu242	Total
C	U9	45,8	54,2	0,0	0,0	0,0	0,0	100,0
	U Fe	99,7	0,3	0,0	0,0	0,0	0,0	100,0
	U Fe	99,7	0,3	0,0	0,0	0,0	0,0	100,0
D	X1X	94,8	5,2	0,0	0,0	0,0	0,0	100,0

ENDF/B-VI

		U235	U238	Pu239	Pu240	Pu241	Pu242	Total
A	R2	77,8	22,2	0,0	0,0	0,0	0,0	100,0
	ZONA2	2,4	46,4	44,0	3,9	3,0	0,2	100,0
B	7A	8,2	50,7	38,7	1,3	1,0	0,0	100,0
	7B	11,9	56,2	30,1	0,9	0,8	0,0	100,0
	9C1	73,9	26,1	0,0	0,0	0,0	0,0	100,0
	9C2	13,2	47,2	37,5	1,3	0,8	0,0	100,0
C	C Ref	1,9	56,7	38,0	1,7	1,6	0,0	100,0
	Pu C SS	0,0	0,0	98,1	1,2	0,8	0,0	100,0
	RSR	1,5	42,7	52,1	2,1	1,5	0,0	100,0
	U9	48,0	52,0	0,0	0,0	0,0	0,0	100,0
	U Fe	99,7	0,3	0,0	0,0	0,0	0,0	100,0
	U Fe Leak	99,7	0,3	0,0	0,0	0,0	0,0	100,0
D	X1X	95,2	4,8	0,0	0,0	0,0	0,0	100,0

Table 3

Sensitivity coefficients using the modified formalism (%)

	JEF2						ENDF/B-VI					
R2	1	2	3	4	5	total	1	2	3	4	5	total
U235	6,0	62,3	6,8	0,9	0,2	76,2	6,1	63,7	6,9	0,9	0,2	77,8
U238	0,0	0,9	18,5	3,4	1,0	23,8	0,0	0,8	17,2	3,3	0,9	22,2

Table 3 (Continued)

Sensitivity coefficients using the modified formalism (%)

			JEF2						ENDF/B-VI					
	Zona2		**1**	**2**	**3**	**4**	**5**	**total**	**1**	**2**	**3**	**4**	**5**	**total**
A		U235	0,3	1,8	0,2	0,0	0,0	2,3	0,3	1,9	0,2	0,0	0,0	2,4
		U238	0,0	1,7	37,6	7,3	2,3	48,9	0,0	1,6	35,6	7,1	2,1	46,4
		Pu239	3,4	32,2	5,5	0,8	0,1	42,0	3,6	33,8	5,6	0,8	0,2	44,0
		Pu240	0,0	2,0	1,4	0,2	0,1	3,7	0,0	2,1	1,5	0,2	0,1	3,9
		Pu241	0,4	2,2	0,2	0,0	0,0	2,8	0,4	2,4	0,3	0,0	0,0	3,1
		Pu242	0,0	0,1	0,1	0,0	0,0	0,2	0,0	0,1	0,1	0,0	0,0	0,2
	7A													
		U235	2,0	5,3	0,7	0,1	0,0	8,2	2,0	5,4	0,7	0,1	0,0	8,2
		U238	0,0	1,7	39,2	7,7	2,3	50,8	0,0	1,7	39,1	7,9	2,2	50,8
		Pu239	6,1	26,4	5,3	0,8	0,1	38,7	6,1	26,5	5,2	0,8	0,2	38,7
		Pu240	0,0	0,6	0,5	0,1	0,0	1,3	0,0	0,6	0,5	0,1	0,0	1,3
		Pu241	0,2	0,7	0,1	0,0	0,0	1,0	0,2	0,7	0,1	0,0	0,0	1,0
		Pu242	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	7B													
		U235	1,8	8,7	0,7	0,1	0,0	11,4	1,9	9,1	0,7	0,1	0,0	11,9
		U238	0,0	2,0	44,5	9,2	2,9	58,6	0,0	1,9	42,5	9,1	2,7	56,2
		Pu239	2,9	22,1	2,9	0,4	0,1	28,4	3,1	23,5	3,0	0,5	0,1	30,1
		Pu240	0,0	0,5	0,3	0,1	0,0	0,9	0,0	0,5	0,3	0,1	0,0	0,9
B		Pu241	0,1	0,6	0,0	0,0	0,0	0,7	0,1	0,6	0,1	0,0	0,0	0,8
		Pu242	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	9C1													
		U235	5,5	59,0	6,7	0,9	0,2	72,2	5,6	60,5	6,7	0,9	0,2	74,0
		U238	0,0	1,1	21,6	3,9	1,2	27,8	0,0	1,0	20,2	3,8	1,1	26,0
	9C2													
		U235	1,6	9,7	1,1	0,2	0,0	12,6	1,6	10,2	1,2	0,2	0,0	13,2
		U238	0,0	1,7	38,2	7,3	2,2	49,5	0,0	1,6	36,4	7,1	2,0	47,2
		Pu239	2,6	27,7	4,8	0,7	0,1	35,9	2,7	29,0	4,9	0,7	0,1	37,5
		Pu240	0,0	0,7	0,5	0,1	0,0	1,3	0,0	0,7	0,5	0,1	0,0	1,3
		Pu241	0,1	0,6	0,1	0,0	0,0	0,7	0,1	0,6	0,1	0,0	0,0	0,8
		Pu242	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	CRef													
		U235	0,4	1,3	0,1	0,0	0,0	1,8	0,4	1,4	0,1	0,0	0,0	1,9
		U238	0,0	2,4	44,7	9,2	3,0	59,3	0,0	2,3	42,6	9,0	2,8	56,7
		Pu239	4,4	27,0	3,6	0,6	0,1	35,7	4,7	28,8	3,8	0,6	0,1	38,0
		Pu240	0,0	0,9	0,6	0,1	0,0	1,6	0,0	0,9	0,6	0,1	0,0	1,7
		Pu241	0,3	1,1	0,1	0,0	0,0	1,5	0,3	1,2	0,1	0,0	0,0	1,6
		Pu242	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	PuCSS													
		Pu239	43,3	45,5	8,0	1,1	0,2	98,1	43,3	45,6	7,8	1,1	0,2	98,0
		Pu240	0,1	0,6	0,4	0,1	0,0	1,2	0,1	0,6	0,4	0,1	0,0	1,2
		Pu241	0,5	0,3	0,0	0,0	0,0	0,7	0,5	0,3	0,0	0,0	0,0	0,8
		Pu242	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Table 3 (Continued)

Sensitivity coefficients using the modified formalism (%)

		JEF2						ENDF/B-VI					
		1	2	3	4	5	total	1	2	3	4	5	total
RSR													
	U235	0,3	1,1	0,1	0,0	0,0	1,5	0,3	1,1	0,1	0,0	0,0	1,5
	U238	0,0	1,7	34,9	6,5	2,0	45,1	0,0	1,6	33,0	6,3	1,8	42,7
	Pu239	5,4	38,3	5,4	0,8	0,1	50,0	5,7	40,0	5,6	0,8	0,2	52,1
	Pu240	0,0	1,1	0,7	0,1	0,0	2,0	0,0	1,2	0,8	0,1	0,0	2,1
	Pu241	0,2	1,1	0,1	0,0	0,0	1,4	0,3	1,1	0,1	0,0	0,0	1,5
	Pu242	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
U9													
	U235	0,6	42,3	2,3	0,4	0,1	45,8	0,6	44,4	2,4	0,4	0,1	48,0
	U238	0,0	2,6	39,0	9,3	3,3	54,2	0,0	2,5	37,3	9,1	3,1	52,0
UFe													
	U235	23,4	71,2	4,4	0,5	0,1	99,7	23,5	71,3	4,3	0,5	0,1	99,7
	U236	0,0	0,0	0,3	0,0	0,0	0,3	0,0	0,0	0,2	0,0	0,0	0,3
UFe Leak													
	U235	23,4	71,2	4,4	0,5	0,1	99,7	23,5	71,3	4,3	0,5	0,1	99,7
	U238	0,0	0,0	0,2	0,0	0,0	0,3	0,0	0,0	0,2	0,0	0,0	0,3
D **X1X**													
	U235	42,6	44,9	6,8	0,8	0,2	95,2	42,7	44,9	6,7	0,8	0,1	95,2
	U238	0,0	0,2	3,8	0,6	0,2	4,8	0,0	0,2	3,8	0,6	0,2	4,8

1 : Eth - 10 kEv   2 : 10 keV - 2 MeV   3 : 2 MeV - 4 MeV 4 : 4 MeV - 7 MeV 5 : 7 MeV - 20 MeV

A : MASURCA   B : SNEAK   C : ZPR   D : FCA

The results obtained with the Keepin formalism are shown in Table 4, and are in qualitative agreement with those obtained by A. D'Angelo [19] who has considered 10 integral data (out of our 13 integral data used in this study) from SNEAK and ZPR, using the same Keepin formalism but in with a different code system (CCCR) and a different nuclear data library (CARNAVAL IV).

Table 4

Relative adjustment of ν_d (Keepin formalism)

JEF2	U235	U238	Pu239
$\Delta\nu_d/\nu_d$ %	-1.78	-0.59	+0.82
Uncertainty after adjustment %	± 0.70	± 1.20	± 1.10

ENDF/B-VI	U235	U238	Pu239
$\Delta\nu_d/\nu_d$ %	-1.92	+ 5.55	+ 1.77
Uncertainty after adjustment %	± 0.80	± 1.50	± 1.30

	$1-\sqrt{2/N}$	χ^2/N	$1+\sqrt{2/N}$
JEF2	0.608	0.482	1.392
ENDF/B-VI	0.608	0.667	1.392

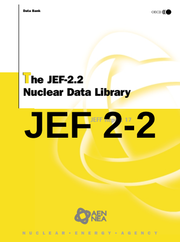

Table 4 (Continued)

Average delayed yields fors fast mockups

JEF2	U235	U238	Pu239
ν_d (pcm)	1628 ± 11	4663 ± 56	650 ± 7

ENDF/B-VI	U235	U238	Pu239
ν_d (pcm)	1634 ± 13	4531 ± 68	655 ± 9

Results of the adjustment calculations on β_{eff} (Keepin formalism)

JEF2

Experiences	E	C after adjustment	C before adjustment
R2	719 ± 17	741.2	730.0 ± 3.9
Zona2	345 ± 8	348.6	348.7 ± 2.0
7A	395 ± 12	387.8	387.4 ± 2.1
7B	429 ± 13	437.8	436.4 ± 2.7
9C1	748 ± 24	748.9	738.1 ± 4.0
9C2	416 ± 19	399.5	398.7 ± 2.2
CRef	381 ± 8	380.8	380.5 ± 2.5
PuCSS	222 ± 4	221.8	223.6 ± 2.5
RSR	335 ± 7	328.6	328.9 ± 1.9
U9	706 ± 14	726.3	717.9 ± 4.8
UFeRef	667 ± 13	674.5	662.6 ± 4.6
UFeLeak	672 ± 13	674.4	662.6 ± 4.6
X1X	738 ± 15	766.7	753.2 ± 4.9

Values in pcm   E : Experience   C : Calculation

ENDF/B-VI

Experiences	E	C after adjustment	C before adjustment
R2	719 ± 17	728.9	727.0 ± 4.7
Zona2	345 ± 8	336.6	347.9 ± 2.4
7A	395 ± 12	372.5	384.6 ± 2.7
7B	429 ± 13	419.1	433.6 ± 3.2
9C1	748 ± 24	733.8	734.0 ± 4.6
9C2	416 ± 19	384.1	395.2 ± 2.5
CRef	381 ± 8	365.3	379.1 ± 2.9
PuCSS	222 ± 4	220.2	224.1 ± 2.7
RSR	335 ± 7	318.1	328.3 ± 2.2
U9	706 ± 14	695.5	709.3 ± 5.6
UFeRef	667 ± 13	678.2	665.4 ± 5.4
UFeLeak	672 ± 13	678.1	665.4 ± 5.4
X1X	738 ± 15	767.4	755.1 ± 5.7

Values in pcm   E : Experience   C : Calculation

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he results obtained with the modified Keepin formalism (Table 5) show an increase of ν_d in the third energy for ^{235}U and in the second and third groups for ^{239}Pu. This tends to confirm the indications of the Lendel relative to the gradient for $\nu_d(E)$, but should not be considered to be conclusive given the small sensitivities of the fast experimental data in the first energy range. Concerning ^{238}U, it is difficult to conclude.

It has to be noted that, concerning the adjustment with JEF2 data : first, it has been performed with an integral dispersion matrix in which the covariance terms have been provisionaly neglected, second, the reduced χ^2 value lies outside the theoretical limits. The last point suggests that the uncertainties on apriori values (integral and microscopic data) are probably overestimated.

Table 5
Relative adjustment on ν_d (Modified formalism)

U235

JEF2	Eth. - 10 keV	10 keV - 2 MeV	2 MeV - 4 MeV	4 MeV - 7 MeV	7 MeV- 20 MeV
$\Delta\nu_d/\nu_d$ %	- 1.27	- 1.75	- 0.85	- 0.55	- 0.12
Uncertainty after ajustment %	± 1.50	± 1.10	±1.90	± 2.70	± 3.40
ENDF/B-VI					
$\Delta\nu_d/\nu_d$ %	- 1.99	- 1.74	- 0.90	- 0.56	- 0.11
Uncertainty after ajustment %	± 1.80	± 1.10	± 2.20	± 3.10	± 3.90

U238

JEF2	Eth. - 10 keV	10 keV - 2 MeV	2 MeV - 4 MeV	4 MeV - 7 MeV	7 MeV- 20 MeV
$\Delta\nu_d/\nu_d$ %	- 0.10	- 0.23	- 0.67	- 0.54	- 0.43
Uncertainty after ajustment %	± 2.70	± 2.60	± 1.60	± 3.10	± 4.00
ENDF/B-VI					
$\Delta\nu_d/\nu_d$ %	+ 0.76	+ 1.61	+ 5.80	+ 2.80	+ 1.80
Uncertainty after ajustment %	± 3.10	± 3.00	± 2.00	± 3.50	± 4.60

Pu239

JEF2	Eth. - 10 keV	10 keV - 2 MeV	2 MeV - 4 MeV	4 MeV - 7 MeV	7 MeV- 20 MeV
$\Delta\nu_d/\nu_d$ %	+ 0.14	+ 1.13	+ 0.50	+ 0.33	+ 0.21
Uncertainty after ajustment %	± 1.70	± 1.50	± 1.90	± 2.70	± 3.40
ENDF/B-VI					
$\Delta\nu_d/\nu_d$ %	+ 0.51	+ 2.01	+ 0.84	+ 0.55	+ 0.34
Uncertainty after ajustment %	± 1.90	± 1.70	± 2.20	± 3.10	± 3.90

Table 5 (Continued)

Relative adjustment on ν_d (Modified formalism)

	$1-\sqrt{2/N}$	χ^2/N	$1+\sqrt{2/N}$
JEF2	0.608	0.465	1.392
ENDF/B-VI	0.608	0.620	1.392

Results of the ajustment calculation on β_{eff} (Modified formalism)

JEF2

Experiences	E	C before ajustment	C after ajustment
R2	719 ± 17	741.2	730.8 ± 4.3
Zona2	345 ± 8	348.7	348.9 ± 2.0
7A	395 ± 12	387.5	387.1 ± 2.2
7B	429 ± 13	437.6	436.4 ± 2.8
9C1	748 ± 24	748.6	738.6 ± 4.3
9C2	416 ± 19	399.1	398.5 ± 2.2
CRef	381 ± 8	380.8	380.6 ± 2.5
PuCSS	222 ± 4	221.8	223.2 ±2.1
RSR	335 ± 7	328.6	329.1 ± 1.9
U9	706 ± 14	725.5	717.4 ± 4.9
UFeRef	667 ± 13	674.4	663.7 ± 4.5
UFeLeak	672 ± 13	674.3	663.7 ± 4.5
X1X	738 ± 15	763.3	752.2 ± 5.1

Values in pcm E : Experience C : Calculation

ENDF/B-VI

Experiences	E	C before ajustment	C after ajustment
R2	719 ± 17	729.1	727.8 ± 5.0
Zona2	345 ± 8	337.0	347.4 ± 2.3
7A	395 ± 12	387.5	399.3 ± 2.7
7B	429 ± 13	419.1	432.3 ± 3.1
9C1	748 ± 24	733.5	734.1 ± 5.0
9C2	416 ± 19	384.0	394.2 ± 2.5
CRef	381 ± 8	365.5	377.9 ± 2.8
PuCSS	222 ± 4	220.3	223.0 ± 2.5
RSR	335 ± 7	318.3	327.6 ± 2.2
U9	706 ± 14	694.7	706.5 ± 5.6
UFeRef	667 ± 13	678.3	666.5 ± 5.2
UFeLeak	672 ± 13	678.2	666.5 ± 5.2
X1X	738 ± 15	767.9	756.5 ± 5.9

Values in pcm E : Experience C : Calculation

ONCLUSIONS

appears from the adjustment, even if some problems are still unresolved, that the experimental integral data are consistent both with themselves and also with the calculated values.

This is an important point as it has been carefully verified that both formalisms and their related algorithms give identical results when consistent ν_d data are introduced as input data. In addition the results of the adjustment in the fast range are significant since the number of integral data is sufficient with respect to the number of parameters that have been adjusted.

The trends indicated by these results should be accepted in the fast energy range, namely with respect to JEF2.2 :

^{235}U : decrease by more 1% ($\nu_d \sim 1.63\ 10^{-2}$);

^{238}U : no change ($\nu_d \sim 4.66\ 10^{-2}$);

^{239}Pu : increase by a fraction of percent ($\nu_d \sim 0.65\ 10^{-2}$).

The uncertainties after adjustment are very close to those required by J.ROWLANDS [20].
Concerning the energy dependence of ν_d more thermal data is required in order to reach a definitive conclusion. The consideration of thermal data is also justified by the importance of the application of these for the use of MOX fuel.

The integral experiments considered during this study provide a very scarce information about the higher Pu isotopes and additional microscopic and/or integral experimental information is required.

For the minor Actinides such as ^{237}Np and ^{241}Am (?) the motivations for a substantial and organized research effort are considerable :

- from the point of view of industrial application both nuclei are candidates for incineration ;
- from the point of view of Nuclear Physics both are odd Z nuclei without any odd-even effect. Consequently both are good candidates for an additional validation of the Lendel model concerning the specific point of the competition with prompt neutron emission.

All of these encouraging results are a partial validation of the modified KEEPIN formalism proposed by A.FILIP, and show that the model by LENDEL and coworkers is a helpful improvement which simplifies in a consistent way the calculations required for widespread applications. Nevertheless some improvements are necessary and this is one of the objectives currently being satisfied at Cadarache with the Phd thesis by V. ZAMMIT.

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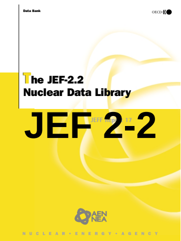

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