^{239}Pu Prompt Fission Neutron Spectra Impact on a Set of Criticality and Experimental Reactor Benchmarks

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A large set of nuclear data are investigated to improve the calculation predictions of the new neutron transport simulation codes. With the next generation of nuclear power plants (GEN IV projects), one expects to reduce the calculated uncertainties which are mainly coming from nuclear data and are still very important, before taking into account integral information in the adjustment process.

In France, future nuclear power plant concepts will probably use MOX fuel, either in Sodium Fast Reactors or in Gas Cooled Fast Reactors. Consequently, the knowledge of ^{239}Pu cross sections and other nuclear data is crucial issue in order to reduce these sources of uncertainty. The Prompt Fission Neutron Spectra (PFNS) for ^{239}Pu are part of these relevant data (an IAEA working group is even dedicated to PFNS) and the work presented here deals with this particular topic.

The main international data files (i.e. JEFF-3.1.1, ENDF/B-VII.0, JENDL-4.0, BRC-2009) have been considered and compared with two different spectra, coming from the works of Maslov and Kornilov respectively. The spectra are first compared by calculating their mathematical moments in order to characterize them. Then, a reference calculation using the whole JEFF-3.1.1 evaluation file is performed and compared with another calculation performed with a new evaluation file, in which the data block containing the fission spectra (MF=5, MT=18) is replaced by the investigated spectra (one for each evaluation).

A set of benchmarks is used to analyze the effects of PFNS, covering criticality cases and mock-up cases in various neutron flux spectra (thermal, intermediate, and fast flux spectra). Data coming from many ICSBEP experiments are used (PU-SOL-THERM, PU-MET-FAST, PU-MET-INTER and PU-MET-MIXED) and French mock-up experiments are also investigated (EOLE for thermal neutron flux spectrum and MASURCA for fast neutron flux spectrum).

This study shows that many experiments and neutron parameters are very sensitive to the PFNS, in particular for high leakage thermal criticality cases for which the discrepancy between international evaluation files spectra and Kornilov spectra can reach 800 pcm. A neutronic analysis is proposed to explain this large discrepancy. For fast spectrum cases, Maslov's and Kornilov's spectra have a negative effect, between some dozens of pcm to around 300 pcm.

I. INTRODUCTION

The prompt fission neutron spectra (PFNS) are crucial parameters in neutronic calculations. They are actually very important either for eigenvalue calculations, or for radiation shielding calculations because deep penetrating neutrons are born in the fast energy range and any change may have large effects on neutron flux far from the source.

The international evaluation files use the same theoretical model in general. But some very different spectra are proposed by other evaluators. The aim of this study is to evaluate the impact of these kinds of spectrum on some typical benchmarks. The article propose to evaluate their effect with the Monte Carlo transport code TRIPOLI-4 [1]. The considered benchmarks are taken from international databases (ICSBEP [2], IRPHE [3]) or MASURCA and EOLE French CEA mockup experimental devices.

In the first section, the article shows graphical comparisons or mathematical characterizations of the different spectra. Then, the TRIPOLI-4 k_{eff} calculation results with all considered spectra are presented. Finally, an analysis is proposed for some particular thermal cases for which one of the spectra has large effects.

II. DIFFERENT ^{239}Pu SPECTRA (PFNS)

A set of different spectra has been studied. The general principle of this study is to use the JEFF-3.1.1 [4] library as a reference, and to replace in the ^{239}Pu evaluation file the original prompt neutron fission spectra by either the

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BRC-2009 [5], JENDL-4.0 [6], ENDF/B-VII.0 [7], and Maslov and Kornilov [8] spectra.

As a first consideration, it has to be noticed that all international evaluations use a Madland-Nix model to get the final tabulated prompt spectra. They don't use exactly the same parameters (number of chance of fission for example) and some improvements are added (fragments' kinetic energy distribution for example). These spectra are very similar. On the contrary, Maslov and Kornilov spectra are very different and are based on systematics. All the spectra are presented in Fig. 1. They are compared to a Maxwellian distribution with temperature equivalent to 1.3719 MeV.

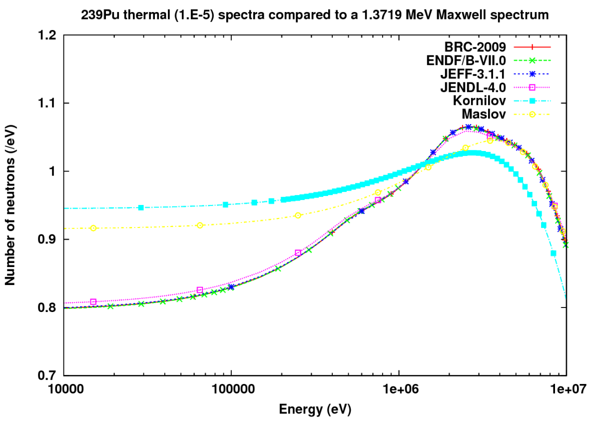

FIG. 1. Kornilov spectrum, Maslov spectrum and other international evaluation files spectra (MF=5, MT=18) compared to a Maxwellian distribution.

The spectra are characterized by their mathematical moments, μ_n (where $\chi(E)$ is the fission spectrum and E is the outgoing neutron energy)

$$\mu_n = \int E^n \times \chi(E) \times dE. \qquad (1)$$

The first moment (the mean energy) is shown in table I for different incident neutron energies. The incident energy grids are very different from one evaluation to another and holes correspond to undefined spectra.

TABLE I. First moment of energetic distributions for all spectra and for different incident energies, in MeV.

Incident energy	1. 10^{-11} MeV	1. 10^{-1} MeV	1. MeV	2. MeV	5. MeV
BRC-2009	2.113	2.116	2.139	2.165	2.236
ENDF/B-VII.0	2.112		2.138	2.163	2.236
JEFF-3.1.1	2.112	2.115	2.140	2.168	2.226
JENDL-4.0	2.116	2.122	2.140	2.165	2.237
Maslov	2.092		2.122	2.152	2.242
Kornilov	2.055		2.084	2.115	2.205

The mean energy discrepancy between Kornilov spectrum and JEFF-3.1.1 one is about -2.7 % at 10^{-11} MeV and -2.4 % at 2 MeV. In Maslov's case, the discrepancy equals -1.0 % and -0.8 % at these energies, whereas the maximum discrepancy between all international evaluations are respectively 0.2 % and 0.2 %. In the following sections, only JEFF-3.1.1 spectra are compared to Maslov and Kornilov ones because all evaluations files (ENDF/B, JEFF, JENDL, BRC) spectra give very close results.

III. FAST, INTERMEDIATE AND THERMAL FLUX EXPERIMENTS

All the presented experiments are characterized by the EALF parameter (Energy of Average Lethargy of Fission) which is defined by

$$EALF = \frac{E_0}{e^{\bar{u}}}, \text{ where } \bar{u} = \frac{\int u \times \Sigma_f(u) \times \Phi(u) \times du}{\int \Sigma_f(u) \times \Phi(u) \times du}. \qquad (2)$$

This parameter is taken from ICSBEP definitions.

In the following sections, all σ values are standard deviations, in PCM, for k_{eff} or k_{eff}s discrepancies.

A. Fast Flux Spectrum Cases

Some fast flux criticality experiments taken in the ICSBEP database have been simulated. They all belong to the PU-MET-FAST class (Plutonium, Metal, Fast spectrum). The results are shown in Table II. The effect between Maslov or Kornilov spectra and JEFF-3.1.1 spectra has been calculated. EALF is expressed in MeV.

TABLE II. Criticality fast spectrum experiments - JEFF-3.1.1 versus Maslov and Kornilov calculations expressed in PCM.

Experiment	EALF	$k_{eff}(\sigma)$	Maslov (σ)	Kornilov (σ)
PMF001	1.330	1.00046 (12)	-114 (17)	-279 (17)
PMF002	1.330	1.00433 (5)	-116 (7)	-271 (7)
PMF011	0.108	0.99707 (15)	+41 (21)	-17 (21)
PMF022	1.310	0.99810 (7)	-91 (10)	-227 (10)
PMF024	0.699	0.99982 (8)	-4 (10)	-104 (11)
PMF027	0.090	1.00131 (8)	+10 (11)	+0 (11)
PMF029	1.330	0.99747 (7)	-113 (10)	-264 (10)
PMF031	0.223	1.00333 (8)	-1 (11)	-63 (11)

The fast spectrum mockups cases are either taken in IRPHE database or in MASURCA experimental program. The considered IRPHE experiments are the SNEAK7A and SNEAK7B, and the MASURCA results are coming either from CYRANO Pu burning cores program (ZONA 2A, 2B or 2A3 experiments) or from PRE-RACINE program dedicated to Super-Phenix reactor (PRE-RACINE I, IIA or IIB experiments).

As expected, the effect is larger for Kornilov spectra and is negative. Actually, the sensitivity calculations performed with the deterministic system ERANOS/PARIS

TABLE III. Mockup fast spectrum experiments - JEFF-3.1.1 versus Maslov and Kornilov calculations expressed in PCM.

Experiment	EALF	$k_{eff}(\sigma)$	Maslov (σ)	Kornilov (σ)
ZONA2A	0.192	1.00995 (12)	-149 (17)	-310 (17)
ZONA2B	0.117	1.00918 (3)	-148 (4)	-308 (4)
ZONA2A3	0.142	1.01034 (12)	-140 (17)	-282 (17)
PRE-RAC. I	0.085	1.00446 (12)	-67 (17)	-112 (17)
PRE-RAC. IIa	0.089	1.00431 (12)	-74 (17)	-145 (17)
PRE-RAC. IIb	0.094	1.00409 (12)	-57 (17)	-157 (17)
SNEAK7A	0.135	1.01001 (2)	-123 (3)	-285 (3)
SNEAK7B	0.141	1.00466 (2)	-181 (3)	-390 (3)

[9] explain this large effect. The sensitivity to high energy (1 MeV and more) is very important and changes in this energy range have a large impact on k_{eff}.

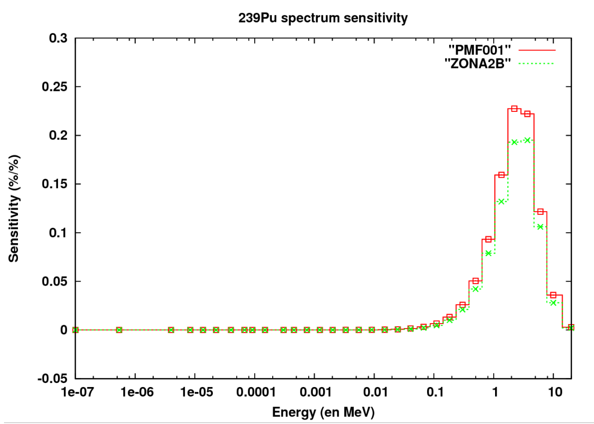

FIG. 2. k_{eff} senstivities on spectrum for ZONA2B and PU-MET-FAST 001 fast flux spectrum experiments.

B. Intermediate Flux Spectrum Cases

The intermediate flux spectrum experiments PU-COMP-INTER-001 (HISS experiments in Hector reactor), PU-MET-INTER-002 (ZPR-6 assembly 10) and PU-MET-MIXED-001 (or BFS-81 experiment) EALF values cover the energy range from 1 eV to 10 keV. In table IV, EALF is given in eV.

TABLE IV. Criticality intermediate spectrum experiments - JEFF-3.1.1 versus Maslov and Kornilov calculations expressed in PCM.

Experiment	EALF	$k_{eff}(\sigma)$	Maslov (σ)	Kornilov (σ)
PCI001	319	1.00860 (11)	-56 (16)	-99 (16)
PMI002	10200	1.03234 (13)	+61 (18)	+85 (18)
PMM001-1	5540	1.00510 (35)	+108 (50)	+200 (49)
PMM001-2	276	1.00470 (20)	+91 (33)	+271 (28)
PMM001-3	61.4	1.00590 (19)	+161 (27)	+332 (29)
PMM001-4	1.34	1.00770 (20)	+98 (29)	+321 (28)
PMM001-5	1.29	1.00719 (19)	106 (26)	+326 (25)

The effect is positive this time. For the PCI case, the effect is negative. The experiment corresponds to a k_∞ "measurement" and the leakage effect analyzed in section IV doesn't occur in this case.

C. Thermal Flux Spectrum Cases

The thermal flux spectrum experiments come either from the ICSBEP database and particularly from the PU-SOL-THERM class (Plutonium, Solution, Thermal spectrum) or from the EOLE French mockup experimental program (MISTRAL 100% MOX high moderation core experiments). EALF is given in eV.

TABLE V. Criticality thermal spectrum experiments - JEFF-3.1.1 versus Maslov and Kornilov calculations expressed in PCM.

Experiment	EALF	$k_{eff}(\sigma)$	Maslov (σ)	Kornilov (σ)
PST001-1	0.089	1.00106 (10)	+411 (14)	+876 (14)
PST001-4	0.154	1.00041 (14)	+394 (20)	+880 (20)
PST001-6	0.367	1.00642 (10)	+366 (14)	+822 (14)
PST004-5	0.054	0.99594 (10)	+328 (14)	+737 (14)
PST005-1	0.055	0.99862 (10)	+318 (14)	+729 (14)
PST005-7	0.068	1.00052 (10)	+318 (14)	+757 (14)
PST006-2	0.053	0.99827 (10)	+294 (14)	+668 (14)
PST007-3	0.272	1.00095 (10)	+373 (14)	+843 (14)
PST007-10	0.107	0.99743 (10)	+388 (14)	+867 (14)
PST012-5	0.043	1.00974 (10)	+54 (12)	+155 (14)
PST012-13	0.043	1.00594 (10)	+50 (14)	+173 (14)

The effect of PFNS on PU-SOL-THERM 001, 004, 005, 006 and 007 is very important by using the Kornilov spectrum. This huge effect is due to large leakage. Some other explanations will be given in the next section. For other cases, the discrepancy is much lower.

TABLE VI. EOLE mockup thermal spectrum experiments - JEFF-3.1.1 versus Maslov and Kornilov calculations expressed in PCM.

Experiment	$k_{eff}(\sigma)$	Maslov (σ)	Kornilov (σ)
MISTRAL-2	1.00726 (4)	+37 (6)	+74 (6)
MISTRAL-3	1.00767 (4)	+54 (6)	+110 (6)

For EOLE mockup experiments, the impact of the Kornilov and Maslov spectra is less important. Although leakage are quite important in these configurations, the fissile material is different (MOX fuel). The fast neutron fissions effect contributes to the reduction of the discrepancies (ϵ factor in section IV).

IV. PHYSICAL ANALYSIS

An analysis has been performed to understand the huge effect of Kornilov spectrum in some thermal flux cases.

The analysis is based on k_{eff} and k_∞ expressions

$$k_{\text{eff}} = \frac{k_\infty}{1 + M^2 \times B^2}, \quad (3)$$

where M^2 is the migration area, B^2 is the buckling and k_∞ can be written by the well known Fermi's formula

$$k_\infty = \epsilon \times p \times f \times \eta, \quad (4)$$

where ϵ is the fast energy range amplification factor, p is the probability to escape to absorption in epithermal energy range, f is the probability to be absorbed in the fissile zones in the thermal energy range, η is the mean number of fission neutrons per thermal absorption.

Table VII shows each of these factors (and ν, number of neutrons per fission) in the case of JEFF-3.1.1 PFNS and Kornilov PFNS for PU-SOL-THERM-001 case 1.

TABLE VII. PU-SOL-THERM-001 k_∞ - JEFF-3.1.1 versus Kornilov calculations expressed in PCM.

Factor	JEFF-3.1.1	σ (pcm)	Kornilov	σ (pcm)
ϵ	1.06448	13	-14	13
p	0.89366	1	+29	1
f	0.91994	12	0	11
ν	2.86787	34	-6	34
η	1.92387	12	-3	12
k_{inf}	1.68364	32	+28	31

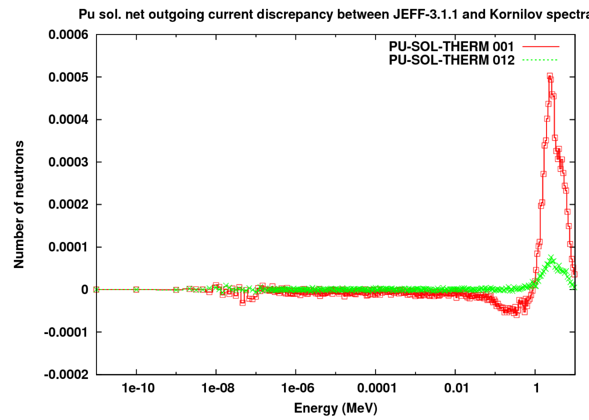

FIG. 3. Fissile zone outgoing net current discrepancy between JEFF-3.1.1 and Kornilov spectra calculations.

The table shows that all the k_∞factors (and k_∞ itself) are very close. In Fig. 3, the fissile zone outgoing net current discrepancy between the two calculation cases is plotted. For the PU-SOL-THERM-001 case, more neutrons leave the fission zone with the JEFF-3.1.1 spectrum and are absorbed in the water reflector. As long as B^2 does not change, the reactivity effect is due to migration area change. This can be explained by the decrease of the ^{1}H elastic cross section above 1 MeV. Actually, the decrease of the mean neutron energy with Kornilov spectrum leads to a increase of this cross section, and consequently a decrease of the migration area.

V. CONCLUSION

This work has shown that the Prompt Fission Neutron Spectra in BRC-2009, ENDF/B-VII.0, JEFF-3.1.1 and JENDL-4.0 are very close to each other and that the calculated effective multiplication factors on a set of selected benchmarks are slightly affected by these different evaluations.

On the contrary, the Maslov and Kornilov spectra may have huge effect for some particular configurations. In particular, the calculated impact on the effective multiplication factor can reach +800 pcm in PU-SOL-THERM experiments (with high leakage level) and -300 pcm in fast spectrum experiments, either for ICSBEP benchmarks or CEA/MASURCA mockup benchmarks.

A sensitivity calculation has been performed and should be soon used for a deeper uncertainty analysis. New PFNS covariance data will be evaluated to achieve this work.

[1] F. Malvagi *et al.*, PROCEEDINGS OF ICMPP 2011 (2011).
[2] J.B. Briggs *et al.,* ICSBEP: INTERNATIONAL CRITICALITY AND SAFETY BENCHMARKS EVALUATION PROJECT, September 2005 Edition NEA/NSC/DOC (95)03 (2005).
[3] J.B. Briggs *et al.,* INTERNATIONAL HANDBOOK OF EVALUATED REACTOR PHYSICS BENCHMARK EXPERIMENTS,

March 2010 Edition NEA/NSC/DOC(2006)1 (2010).

[4] A. Santamarina *et al.*, The JEFF-3.1.1 Nuclear Data Library - Validation results from JEF-2.2 to JEFF-3.1.1, JEFF Report 22 (2009).

[5] P. Romain, New neutron evaluation for actinides with the TALYS code: first validation tests, **JEF-DOC 1266** (2008).

[6] K Shibata *et al.*, J. Nucl. Sci. Technol. **48**, 1 (2011).

[7] M.B. Chadwick *et al.*, Nucl. Data Sheets **107**, 2931 (2006).

[8] R. Capote *et al.*, Summary report, consultants' meeting on Prompt Fission Neutron Spectra of major actinides, IAEA INDC(NDS)-0541 (2008).

[9] R. Letellier, C. Suteau, D. Fournier, J.M. Ruggieri, Il Nuovo Cimento C **33**, 121 (2010).