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Research Article

Effects of evaluated nuclear data libraries on the calculation results for fuel burnup with minor actinides in a VVER reactor*

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Abstract

The paper deals with assessing the effects of the ENDF/B-VI.8, ENDF/B-VII.0, JEFF 3.1 and JEFF 3.1.1 nuclear data libraries on the results of calculating a number of functionals for a system based on a VVER reactor with fuel with a large fraction of minor actinides (up to 10%). Key estimates have been obtained for the errors introduced by libraries in calculations of systems with minor actinides (MA) based on a VVER-1200 reactor:

– for reactivity, $\sigma_\rho = 0.3\ \beta_{eff}$;
– for isotopic compositions with minor actinides, ≤ 5% (the error for each particular isotope is different);
– for the total mass of accumulated MAs, $\varepsilon_m = 0.8\%$.

Conclusions have been made with respect to the need for the further refinement of the library MA data proceeding from the nature of the calculation tasks that dictate the requirements for the accuracy of nuclear constants. It has been shown that systems based on VVER-1000/1200/1300 reactors with MAs need to be calculated using several libraries of evaluated nuclear data created at different organizations and based on the largest possible number of non-recurrent sets of experimental data.

Keywords

minor actinides, evaluated nuclear data libraries, nuclear fuel, burnup, VVER reactor, Monte Carlo method, calculation accuracy

Problem statement

At the present time, neutronic calculations for the burnup of nuclear fuel using minor actinides (Np, Am, Cm) occupy a specific niche in the scope of R&D on advanced nuclear fuel cycles. The importance of such calculations is explained by the fact that there is a consensus about the need for disposal of minor actinides due to their

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high radiotoxicity and heat deposition values with rather lengthy half-lives. Meanwhile, no MA disposal concept has been chosen yet (IAEA-TECDOC-693, 1993). Estimated quantities of accumulated MAs in different reactors have been available since quite a long time ago (Kolobashkin et al. 1983), still reliable libraries of evaluated nuclear data with exhaustive information on the cross-sections for MAs are required to estimate the burnup of nuclear fuel with a high BOL MA concentration.

The studies to estimate the effects of data from different libraries on the calculation results can be divided into two categories:

- purely computational activities when discrepancies among evaluated data libraries are investigated in the course of simulating any system with fissionable materials without a reference to the experiment;
- activities with an experiment where experimental data on any system are compared against the computational model built using different libraries.

Calculations allow estimating rapidly the effects of libraries on the result, though there is a potential, however, for a situation to take place when some of the cross-sections are in a good agreement between libraries but disagree to a large extent with the experiments. In Blokhin et al. 2008, for example, the whole set of the experimentally obtained parameters (integrated radiation capture cross-section for ^{243}Am, resonance fission integrals for ^{237}Np, ^{240}Pu, ^{242}Pu, ^{241}Am and ^{243}Am) differed greatly from what was stated in the verified libraries. Such mismatch between the computational expectations and the actual physics of the reactor core is unnoticeable without an experiment, so any modern system with MAs under design requires to be mandatorily verified by experiments at critical facilities. Normally, such disagreements are observed if one and the same set of initial data was used to build different libraries, or the set in question was not adjusted when a new library was built based on the previous one. Such inheritances are often a common practice and are easily recognizable in considering changes for versions of any evaluated nuclear data library (McLane V and Members of the Cross Section Evaluation Working Group 1996; Chadwick et al. 2006).

Unfortunately, the issue of the effects from evaluated nuclear data libraries in calculations of fuel with minor actinides is neglected in most papers. One library is usually selected for calculations, and no information on the selected library is occasionally provided. Where problems exist with data on the cross-sections for minor actinides, negligence of disagreements among libraries and the absence of calculations based on several libraries reduces the confidence in the findings.

This paper offers an attempt to estimate the effects of differences among evaluated nuclear data libraries concerning the calculated functionals when simulating the burnup of fuel with minor actinides in a system based on a VVER-1200 reactor, including the dynamics of reactivity in the course of fuel burnup, the change in the mass of minor actinides, and their isotopic composition. Obtaining uncertainties for the calculated functionals makes it possible to estimate the accuracy of simulating fuel cycles with a content of minor actinides in a VVER reactor facility.

Computational model

The problem at hand requires a major fraction of minor actinides (about 10% in this study) to demonstrate the effects of evaluated nuclear data libraries on the result. Based on this, the simulated fuel cycle needs to have two peculiarities:

- an external inflow of minor actinides into the cycle from a VVER reactor (preferably with a fixed composition);
- high fuel enrichment for keeping k_∞ not lower than the subcritical level to bring the model closer to the conditions of an actually operating reactor.

The paper considers a fuel cycle the flowchart for which is presented in Fig. 1.

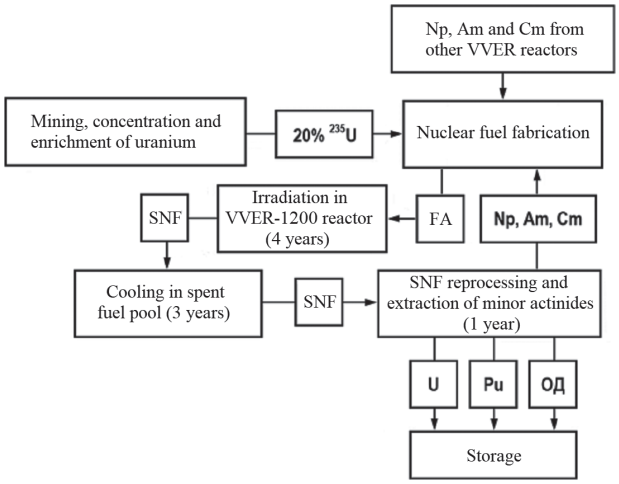

Figure 1. Flowchart of a fuel cycle for a thermal neutron reactor with recirculation of minor actinides.

Since the purpose of the study is to obtain uncertainties of estimated functionals arising due to the difference in the information on MAs in different libraries of evaluated nuclear data, the computational model needs to allow the required uncertainties to be obtained with the smallest possible contribution from the other factors. A 2D VVER-1200 FA model has been therefore selected in an infinite multiplying environment without criticality control methods – this cuts off the effects from burnable absorbers and boric acid in the coolant, as well as spatial effects and neutron leakage representative of a real reactor core. The exact neutron leakage value for VVER-1200 reactors depends on the peculiarities of the peripheral FA loading, so an average leakage value of 2% was adopted for the study (k_∞ in the undertaken calculations does not decrease to below 1.02). The following refueling pattern was implemented for the correct control of k_∞ in the model: the fuel elements are

divided into four groups with a variable fuel burnup depth, the difference in the burnup depths corresponds to one year of residence inside the reactor core, and the fuel elements in different groups are distributed uniformly within the FA volume for reducing the heterogeneous effects.

After the reactor life ends, fuel with the highest burnup depth is replaced for fresh fuel. The isotopic composition of fresh fuel is formed as follows: MAs from the previously unloaded SNF after four years of cooling are added into the uranium with a 20% ^{235}U enrichment (in accordance with the IAEA standards) (to simplify the model, it is assumed that the four-year cooling takes place 'instantaneously'), as well as MAs from other VVER-1200 reactors. A preliminary estimation was undertaken for the annual maximum flow of MAs that can be loaded into the VVER-1200 reactor along with the fuel with a 20% ^{235}U enrichment, without the k_∞ reduction to below 1.02 in the process of burnup; this corresponds to the annual MA generation in 23 VVER-1200 reactors (16.8 kg of MAs per one FA). The isotopic composition of the externally loaded MAs was also determined in advance and found to meet the composition of the MAs unloaded after four-year irradiation of the VVER-1200 FAs with a 4.95% fuel enrichment (Table 1). The density and total quantity of heavy nuclei in fresh fuel remain the same and the added minor actinides replace the ^{235}U and ^{238}U nuclei while the enrichment remains also the same.

Table 1. Isotopic composition of MAs loaded into FAs from the outside.

Isotope	^{237}Np	^{241}Am	^{243}Am	^{243}Cm	^{244}Cm	^{245}Cm	^{246}Cm
atm. %	53.36	25.09	14.96	0.05	5.96	0.53	0.05

At the beginning of the calculations, the FA model contains fuel with a burnup that corresponds to the steady-state mode of the VVER-1200 reactor refueling and is replaced further for fresh fuel based on 20% of ^{235}U with the MA addition. The rated power is 19.75 MW/FA, and the irradiation time and the cooling time are 1460 days each. The overall number of the reactor life cycles is 30. Simulation of multiple refueling with accumulation of minor actinides will make it possible to implement a cumulative effect for all of the existing disagreements among the evaluated nuclear data libraries.

The following parameters were controlled in the calculations: k_∞ at the beginning and at the end of the reactor life, and the MA mass and isotopic composition.

The calculations were performed based on the Serpent 2.1.32 neutronic simulation code (VTT, Finland) (Leppaanen 2015) using the ENDF/B-VI.8, ENDF/B-VII.0, JEFF 3.1 and JEFF 3.1.1 evaluated nuclear data libraries supplied by the code manufacturer (Leppaanen and Viitanen 2013).

Calculation results

Following the fuel cycle calculations (Fig. 1), isotopic compositions of the unloaded SNF and the BOL and EOL reactivity dynamics were obtained from 30 consecutive fuel replacements using different evaluated nuclear data libraries.

Unfortunately, open publications lack experimental data on irradiation of uranium-oxide fuel with a high content of MAs in thermal and fast spectra. Therefore, the average value of functionals and their deviation for each library was calculated in the study to estimate the effects of evaluated nuclear data libraries on the result.

The isotopic composition of the unloaded SNF with minor actinides after 5 and 30 reactor life cycles is presented in Tables 2, 3. The fifth reactor life cycle was selected because spent fuel with the initial 20% enrichment and a high content of MAs is withdrawn for the first time at its end. Apart from the MA composition, data is additionally provided on ^{234}U and ^{236}U since these nuclides are additionally accumulated in a large quantity due to a high level of fuel enrichment. No ^{234}U and ^{236}U are taken into account in the total amount of minor actinides.

It can be seen from Tables 2, 3 that the discrepancy among the library data does not exceed 5 % for ^{237}Np, all plutonium isotopes, ^{243}Am, and ^{243}Cm – ^{246}Cm. This makes sense since the above isotopes are accumulated in significant quantities which levels off the discrepancy in the cross-sections among libraries. Such effect is especially noticeable when comparing the discrepancies between life cycles 5 and 30. ^{241}Am is somewhat out of line with the statistics since its thermal region cross-sections in the JEFF-3.1 and JEFF-3.1.1 libraries are incorrect (Leconte 2020). The discrepancies do not exceed 4% for ^{249}Bk, ^{249}Cf and ^{250}Cf.

No anticipated cumulative effect is observed from the accumulation of discrepancies among the bases when calculating a fuel cycle with recirculation of minor actinides. This conclusion is also confirmed by the dynamics of the minor actinide accumulation shown in Table 4.

Two conclusions can be made based on the data in Table 4:

- calculations based on different libraries produce systemic deviations: thus, JEFF-based calculations lead to the permanent 'shortage' of the minor actinide mass while ENDF-based calculations result in a certain overestimation against the average value;
- the minor actinide total mass error introduced by the evaluated nuclear data libraries in the calculation of systems based on a VVER-1200 reactor depends slightly on the MA quantity and does not exceed 0.8% when the content of MAs in fuel is small (as in life cycles 1 through 4 when the reactor still contains fuel with no MA addition), so the error will be different.

The MA total mass error is not significant for the open fuel cycle calculations since MAs in this case contribute slightly to the power density and their mass is defined largely by generation on plutonium isotopes (the cross-sections for which are known with a good accuracy). However, when calculating fuel cycles with recirculation of minor actinides, their total mass error is required for estimating correctly the flows of fissionable materials in the fuel cycle.

Table 2. Isotopic composition of minor actinides in unloaded SNF after five reactor life cycles.

Isotope	Nuclei × 10^{24}/cm^3					Δ, %			
	JEFF-3.1	JEFF-3.1.1	ENDF/B-VI.8	ENDF/B-VII.0	Average	JEFF-3.1	JEFF-3.1.1	ENDF/B-VI.8	ENDF/B-VII.0
^{234}U	4.69E-6	4.73E-6	4.56E-6	4.61E-6	4.65E-6	-0.95	-1.75	1.82	0.88
^{236}U	4.00E-4	4.00E-4	4.00E-4	4.01E-4	4.00E-6	0.09	0.08	0.08	-0.25
^{236}Np	7.81E-9	6.02E-9	7.80E-9	7.39E-9	7.25E-9	-7.70	17.05	-7.51	-1.83
^{237}Np	3.15E-4	3.13E-4	3.12E-4	3.13E-4	3.13E-4	-0.60	0.14	0.51	-0.05
^{238}Pu	2.63E-4	2.66E-4	2.58E-4	2.57E-4	2.61E-4	-0.93	-1.74	1.19	1.48
^{239}Pu	2.94E-4	2.94E-4	2.94E-4	2.93E-4	2.94E-4	-0.10	-0.05	-0.14	0.29
^{240}Pu	4.33E-5	4.33E-5	4.31E-5	4.31E-5	4.32E-5	-0.20	-0.20	0.12	0.28
^{241}Pu	3.08E-5	3.08E-5	3.10E-5	3.09E-5	3.09E-5	0.31	0.19	-0.39	-0.10
^{242}Pu	1.96E-5	1.96E-5	1.85E-5	1.87E-5	1.91E-5	-2.68	-2.68	3.14	2.23
^{241}Am	6.31E-5	6.31E-5	7.32E-5	7.27E-5	6.80E-5	7.17	7.24	-7.60	-6.81
^{243}Am	6.65E-5	6.64E-5	6.63E-5	6.64E-5	6.64E-5	-0.14	0.01	0.10	0.02
^{242}Cm	1.04E-5	1.04E-5	1.04E-5	1.04E-5	1.04E-5	-0.07	-0.13	0.07	0.13
^{243}Cm	1.03E-6	1.03E-6	9.97E-7	9.98E-7	1.02E-6	-1.76	-1.79	1.85	1.70
^{244}Cm	9.34E-5	9.35E-5	9.40E-5	9.26E-5	9.34E-5	-0.02	-0.11	-0.67	0.79
^{245}Cm	1.68E-5	1.68E-5	1.68E-5	1.79E-5	1.71E-5	1.60	1.49	1.76	-4.86
^{246}Cm	1.99E-6	1.99E-6	1.98E-6	2.08E-6	2.01E-6	0.91	0.90	1.50	-3.32
^{247}Cm	9.28E-8	9.30E-8	8.96E-8	8.50E-8	9.01E-8	-3.00	-3.18	0.58	5.61
^{248}Cm	1.13E-8	1.14E-8	1.16E-8	1.24E-8	1.17E-8	2.89	2.73	0.66	-6.28
^{250}Cm	2.70E-15	2.72E-15	2.68E-15	2.01E-15	2.53E-15	-6.92	-7.62	-5.99	20.53
^{247}Bk	2.84E-17	2.72E-17	1.14E-17	1.71E-17	2.10E-17	-35.28	-29.45	45.84	18.89
^{249}Bk	2.78E-10	2.79E-10	2.74E-10	2.96E-10	2.81E-10	1.39	0.96	2.69	-5.04
^{248}Cf	4.25E-16	4.22E-16	2.56E-15	1.98E-15	1.35E-15	68.42	68.67	-90.31	-46.78
^{249}Cf	2.13E-10	2.14E-10	2.09E-10	2.18E-10	2.13E-10	0.26	-0.16	1.86	-1.96
^{250}Cf	1.27E-10	1.28E-10	1.23E-10	1.33E-10	1.28E-10	0.58	-0.02	3.44	-4.00
^{251}Cf	7.93E-17	8.06E-17	2.25E-20	5.88E-17	5.47E-17	-45.07	-47.36	99.96	-7.53
^{252}Cf	1.85E-17	1.86E-17	1.30E-20	1.38E-17	1.27E-17	-44.98	-46.41	99.90	-8.51

Table 3. Isotopic composition of minor actinides in unloaded SNF after 30 reactor life cycles.

Isotope	Nuclei × 10^{24}/cm^3					ε, %			
	JEFF-3.1	JEFF-3.1.1	ENDF/B-VI.8	ENDF/B-VII.0	Average	JEFF-3.1	JEFF-3.1.1	ENDF/B-VI.8	ENDF/B-VII.0
^{234}U	8.07E-6	8.11E-6	8.02E-6	8.09E-6	8.07E-6	0.00	-0.53	0.68	-0.15
^{236}U	3.46E-4	3.46E-4	3.47E-4	3.47E-4	3.47E-4	0.16	-0.01	0.01	-0.17
^{236}Np	3.91E-8	2.97E-8	3.89E-8	3.56E-8	3.58E-8	-9.15	17.05	-8.52	0.61
^{237}Np	9.26E-4	9.10E-4	9.09E-4	9.20E-4	9.16E-4	-1.04	0.65	0.79	-0.40
^{238}Pu	5.04E-4	5.06E-4	5.03E-4	5.02E-4	5.04E-4	-0.02	-0.54	0.18	0.38
^{239}Pu	3.27E-4	3.27E-4	3.29E-4	3.28E-4	3.28E-4	0.33	0.12	-0.44	-0.01
^{240}Pu	6.29E-5	6.30E-5	6.30E-5	6.25E-5	6.29E-5	-0.08	-0.25	-0.27	0.60
^{241}Pu	3.62E-5	3.63E-5	3.66E-5	3.63E-5	3.64E-5	0.31	0.22	-0.65	0.12
^{242}Pu	2.69E-5	2.68E-5	2.68E-5	2.69E-5	2.69E-5	0.00	0.15	0.10	-0.25
^{241}Am	1.44E-4	1.43E-4	1.68E-4	1.67E-4	1.56E-4	7.57	7.75	-8.08	-7.25
^{243}Am	1.78E-4	1.77E-4	1.77E-4	1.78E-4	1.77E-4	-0.26	0.23	0.24	-0.20
^{242}Cm	1.87E-5	1.87E-5	1.92E-5	1.91E-5	1.90E-5	1.17	1.11	-1.25	-1.03
^{243}Cm	1.98E-6	1.98E-6	2.00E-6	1.99E-6	1.99E-6	0.25	0.36	-0.38	-0.23
^{244}Cm	3.39E-4	3.39E-4	3.42E-4	3.36E-4	3.39E-4	-0.11	-0.07	-0.78	0.95
^{245}Cm	7.02E-5	7.05E-5	7.06E-5	7.36E-5	7.12E-5	1.38	1.07	0.87	-3.32
^{246}Cm	3.06E-5	3.06E-5	3.05E-5	3.19E-5	3.09E-5	0.93	0.85	1.44	-3.23
^{247}Cm	3.70E-6	3.71E-6	3.37E-6	2.90E-6	3.42E-6	-8.14	-8.43	1.45	15.13
^{248}Cm	1.33E-6	1.34E-6	1.41E-6	1.38E-6	1.37E-6	2.33	1.74	-3.41	-0.66
^{250}Cm	1.08E-12	1.09E-12	1.10E-12	7.61E-13	1.01E-12	-6.75	-8.26	-9.49	24.49
^{247}Bk	6.75E-15	6.60E-15	2.79E-15	5.13E-15	5.32E-15	-26.98	-24.05	47.45	3.58
^{249}Bk	4.38E-8	4.44E-8	4.48E-8	4.42E-8	4.43E-8	1.08	-0.16	-1.10	0.18
^{248}Cf	1.94E-13	1.95E-13	1.24E-12	8.56E-13	6.20E-13	68.71	68.62	-99.25	-38.08
^{249}Cf	6.77E-8	6.83E-8	6.81E-8	6.56E-8	6.74E-8	-0.46	-1.26	-1.05	2.77
^{250}Cf	2.37E-8	2.38E-8	2.32E-8	2.29E-8	2.34E-8	-1.08	-1.87	0.78	2.17
^{251}Cf	4.98E-14	5.06E-14	2.41E-19	3.49E-14	3.38E-14	-47.29	-49.64	100.00	-3.07
^{252}Cf	1.19E-14	1.21E-14	1.05E-19	8.39E-15	8.10E-15	-47.03	-49.48	100.00	-3.49

Fig. 2 presents the change in the reactor BOL and EOL reactivity. The reactivity is presented as the arithmetic mean value from the reactivity values obtained in calculations with different libraries.

The reactivity growth in the initial four reactor life cycles is explained by the fact that fuel with a 20% enrichment and MAs was loaded into the core that operated prior to this with standard VVER-1200 fuel of 4.4 to 4.9%. The gradual BOL and EOL reactivity decrease, as well as the reduction in the reactivity margin are caused by the growing mass of MAs in fuel which operate as burnable absorbers and raw isotopes for production of fissionable thermal neutrons.

Table 4. Total masses of minor actinides withdrawn from one SFA after four-year cooling.

Life cycle	M, kg					$\sigma_{m,}$ kg	$\varepsilon_{m,}$ %
	JEFF-3.1	JEFF-3.1.1	ENDF/B-VI.8	ENDF/B-VII.0	Average		
1	0.78	0.77	0.78	0.78	0.78	0.004	0.47
2	0.75	0.74	0.74	0.75	0.74	0.004	0.52
3	0.70	0.70	0.69	0.70	0.70	0.004	0.59
4	11.28	11.22	11.42	11.46	11.35	0.10	0.86
5	11.97	11.92	12.12	12.15	12.04	0.10	0.80
6	12.33	12.28	12.47	12.50	12.40	0.09	0.75
7	12.52	12.48	12.66	12.69	12.59	0.09	0.71
8	19.67	19.56	19.87	19.94	19.76	0.15	0.78
9	20.12	20.02	20.34	20.40	20.22	0.16	0.77
10	20.34	20.23	20.56	20.62	20.44	0.16	0.76
11	20.47	20.37	20.68	20.75	20.57	0.15	0.75
12	25.41	25.25	25.65	25.74	25.51	0.20	0.77
13	25.72	25.56	25.97	26.07	25.83	0.20	0.77
14	25.86	25.69	26.11	26.20	25.97	0.20	0.77
15	25.95	25.79	26.20	26.30	26.06	0.20	0.76
16	29.43	29.21	29.67	29.80	29.53	0.23	0.77
17	29.66	29.44	29.90	30.03	29.75	0.23	0.76
18	29.75	29.52	29.99	30.12	29.84	0.23	0.77
19	29.82	29.59	30.06	30.19	29.91	0.23	0.77
20	32.29	32.02	32.52	32.68	32.37	0.25	0.77
21	32.45	32.18	32.68	32.84	32.54	0.25	0.76
22	32.52	32.24	32.74	32.91	32.60	0.25	0.77
23	32.57	32.30	32.80	32.95	32.65	0.25	0.76
24	34.34	34.03	34.56	34.74	34.42	0.27	0.77
25	34.47	34.15	34.67	34.86	34.54	0.26	0.76
26	34.51	34.19	34.72	34.91	34.58	0.27	0.77
27	34.55	34.24	34.76	34.94	34.62	0.26	0.76
28	35.84	35.49	36.03	36.24	35.90	0.28	0.77
29	35.93	35.57	36.11	36.32	35.98	0.28	0.77
30	35.96	35.60	36.14	36.35	36.01	0.28	0.77

For illustration, Table 5 presents the EOL reactivity calculation results (based on the data on k_{Γ}) using different libraries.

The data in Table 5 confirm the nature of the disagreements demonstrated earlier in Table 4 based on the example of the total masses of extracted MAs: JEFF libraries give a steadily negative reactivity deviation, as compared with the average value, while ENDF libraries give a steadily positive deviation. This is explained both by the difference in the isotopic composition in each case and by different cross-sections in the bases. The search for the root cause for such differences requires detailed calculations with varying each neutron-nucleus interaction cross-section, forming therefore an individual target for investigation being beyond the scope of this study.

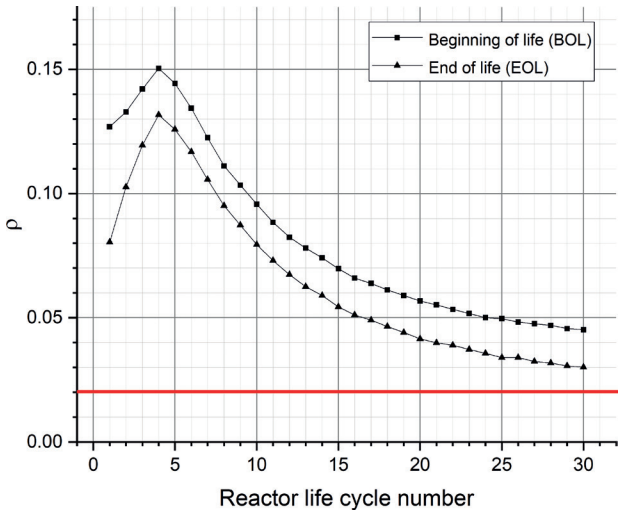

Figure 2. Reactor BOL and EOL reactivity as a function of the life cycle number. The heavy line shows the smallest possible reactivity margin with regard for the infinite FA model.

Considering that the effective fraction of delayed neutrons in the calculations varied about $\beta_{eff} = 5.5\times10^{-3}$, the standard reactivity deviation caused by the evaluated nuclear data libraries, as shown by the data in Table 5, is $\sigma_{\rho} = 0.3\ \beta_{eff}$. With regard for the criterion 3σ, this result is similar to the comparable estimate for the effects of the libraries in simulations of a fast neutron system where the interval of the simulated system's criticality values was ~ β_{eff} (Pandikumar, Gopalakrishnan, Mohanakrishnan 2008).

Conclusions

Three important conclusions can be made from the calculations of a fuel cycle with recirculation of minor actinides using different libraries of evaluated nuclear data.

1. For the main plutonium isotopes, ^{239}Pu – ^{241}Pu, the effects of evaluated nuclear data libraries on the isotopic composition does not exceed 0.6 %. For MAs, unfortunately, the accuracy of data has not reached yet the same level as for ^{239}Pu – ^{241}Pu, so the effects of libraries on the isotopic composition increases by 5 % for the minor actinides accumulated in SNF in a significant quantity (depending on the isotope, this quantity can assume values of 0.2 to 5 %). The total mass of the accumulated MAs is the quantity more tolerant to the effects of libraries, and the error for this does not exceed 0.8 %, which is enough for estimating adequately the mass flows of fissionable materials in the fuel cycle. The effect of the cross-section differences among libraries on reactivity is $\sigma_{\rho} = 0.3\beta_{eff}$ (the value of the same order as the physical weight of one VVER-1200 CPS cluster), which is an acceptable error for the formation of the VVER critical inventory based on fuel with minor actinides.
2. Libraries from one scientific organization can produce steady deviations from the average value. It is important to take this aspect into account when selecting among the evaluated nuclear data libraries to calculate fuel cycles with MAs, so it is recommended that calculations should be done using libraries from different scientific organizations and with different sets of initial experimental data based on which these libraries were created.
3. The accumulation of MAs in significant quantities in fuel leads to a reduction in the disagreements among the results obtained using different libraries.

Table 5. Reactor EOL reactivity.

Life cycle	ρ					ε_ρ, %			
	JEFF-3.1	JEFF-3.1.1	ENDF/B-VI.8	ENDF/B-VII.0	Average	JEFF-3.1	JEFF-3.1.1	ENDF/B-VI.8	ENDF/B-VII.0
1	1.237E-1	1.243E-1	1.287E-1	1.309E-1	1.269E-1	-2.53	-2.06	1.42	3.18
2	1.291E-1	1.311E-1	1.348E-1	1.365E-1	1.329E-1	-2.86	-1.34	1.43	2.77
3	1.391E-1	1.410E-1	1.438E-1	1.443E-1	1.421E-1	-2.09	-0.76	1.23	1.61
4	1.487E-1	1.485E-1	1.520E-1	1.523E-1	1.504E-1	-1.12	-1.27	1.10	1.29
5	1.422E-1	1.429E-1	1.461E-1	1.460E-1	1.443E-1	-1.42	-0.96	1.22	1.16
6	1.321E-1	1.328E-1	1.360E-1	1.365E-1	1.343E-1	-1.67	-1.16	1.22	1.62
7	1.201E-1	1.210E-1	1.237E-1	1.251E-1	1.225E-1	-1.96	-1.23	1.02	2.17
8	1.091E-1	1.093E-1	1.129E-1	1.132E-1	1.111E-1	-1.86	-1.61	1.60	1.87
9	1.019E-1	1.010E-1	1.054E-1	1.053E-1	1.034E-1	-1.42	-2.33	1.94	1.81
10	9.360E-2	9.443E-2	9.709E-2	9.771E-2	9.571E-2	-2.20	-1.33	1.44	2.09
11	8.718E-2	8.717E-2	8.926E-2	9.013E-2	8.844E-2	-1.42	-1.44	0.93	1.92
12	8.096E-2	8.100E-2	8.299E-2	8.474E-2	8.242E-2	-1.77	-1.72	0.69	2.81
13	7.743E-2	7.657E-2	7.900E-2	7.930E-2	7.808E-2	-0.83	-1.93	1.19	1.57
14	7.233E-2	7.215E-2	7.535E-2	7.672E-2	7.414E-2	-2.44	-2.68	1.64	3.48
15	6.882E-2	6.808E-2	7.063E-2	7.155E-2	6.977E-2	-1.36	-2.43	1.24	2.55
16	6.494E-2	6.499E-2	6.648E-2	6.747E-2	6.597E-2	-1.56	-1.48	0.78	2.27
17	6.219E-2	6.243E-2	6.556E-2	6.524E-2	6.385E-2	-2.61	-2.23	2.67	2.17
18	6.015E-2	6.024E-2	6.192E-2	6.252E-2	6.121E-2	-1.73	-1.58	1.17	2.14
19	5.798E-2	5.716E-2	5.996E-2	6.090E-2	5.900E-2	-1.72	-3.12	1.62	3.22
20	5.532E-2	5.500E-2	5.810E-2	5.873E-2	5.679E-2	-2.58	-3.15	2.31	3.42
21	5.419E-2	5.397E-2	5.618E-2	5.643E-2	5.519E-2	-1.82	-2.21	1.78	2.25
22	5.163E-2	5.308E-2	5.392E-2	5.489E-2	5.338E-2	-3.28	-0.56	1.01	2.83
23	5.119E-2	5.002E-2	5.191E-2	5.385E-2	5.174E-2	-1.07	-3.33	0.32	4.08
24	4.931E-2	4.832E-2	5.067E-2	5.186E-2	5.004E-2	-1.45	-3.44	1.25	3.64
25	4.868E-2	4.934E-2	5.013E-2	5.050E-2	4.966E-2	-1.98	-0.65	0.95	1.69
26	4.799E-2	4.719E-2	4.839E-2	4.947E-2	4.826E-2	-0.56	-2.22	0.26	2.51
27	4.614E-2	4.602E-2	4.831E-2	4.994E-2	4.760E-2	-3.08	-3.32	1.48	4.92
28	4.477E-2	4.667E-2	4.742E-2	4.882E-2	4.692E-2	-4.58	-0.53	1.06	4.05
29	4.428E-2	4.471E-2	4.597E-2	4.764E-2	4.565E-2	-3.00	-2.06	0.70	4.36
30	4.319E-2	4.522E-2	4.572E-2	4.680E-2	4.523E-2	-4.51	-0.03	1.08	3.47

The accuracy of the currently available evaluated nuclear data libraries makes it possible to solve problems to calculate mass flows of MAs as part of a nuclear fuel cycle, as well as to determine the dynamics of the reactivity margin in systems based on VVER-1000/1200/1300 reactors in the course of the fuel burnup with MAs. There are however problems with the reactor reactivity coefficient, kinetics and dynamics calculation where the result will be affected to a great extent by disagreements among the libraries in terms of widths and energy maximums of resonances for MAs, yields of fission fragments (especially important is the accuracy of data for the ^{135}Xe, ^{135m}Xe и ^{149}Sm 'neutron poisons' – both of their cross-sections and their yields in the heavy nuclei fission), data on the effective fractions of delayed neutrons in a group-by-group representation, etc. The desired accuracy of calculating the required functionals depends on the problem at hand, and the usability (unsuitability) of the available evaluated nuclear data libraries can be concluded on only after the particular systems with particular problems are explored.

The data presented in this paper with respect to the effects of evaluated nuclear data libraries on the results of calculating the burnup of fuel with minor actinides are not based on the experiment. With regard for the mutual compensations of errors in calculations, as well as the earlier detected effect (Blokhin et al. 2008) from the data reconciliation among libraries in the event of disagreements with the experiment, experiments on the burnup of fuel with MAs need to be undertaken for VVER-based systems with obtaining the isotopic composition after irradiation and unloading.

Further evolution

Neutronic calculations are not limited to only nuclear fuel burnup. The disagreements among evaluated nuclear data libraries affect the calculations of all functionals, so it makes sense to study the effects of libraries on the calculations of the safety parameters and on the results of simulating the kinetics and dynamics of the VVER-1000/1200/1300 reactor facilities based on fuel with the addition of a large fraction of minor actinides.

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