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Checking, processing and verification of nuclear data covariances

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Abstract. The aim of this paper is to present the activities carried out by NEA Data Bank on checking, processing and verification of JEFF-3.3T4 covariances. A picture of the completeness and status of the JEFF-3.3T4 covariances is addressed. The verification of JEFF-3.3T4 covariances is performed with nuclear data sensitivity tool providing the k_{eff} uncertainty as a function of the contributing nuclide-reaction pairings including cross-reaction covariances. A total number of 4501 ICSBEP benchmarks is used in this analysis. This exercise is also extended to covariance libraries such as JENDL-4.0 updated files, ENDF/B-VII.1, SCALE-6.2rev8 and ENDF/B-VIII.0β5, allowing comparison of these results with both the experimental criticality benchmark and different methodologies of evaluation.

1 Introduction

JEFF-3.3T4 [1] is a fully consistent and complete nuclear data library with all data needed and associated covariance information (full covariance information for the main actinides), which can be reliably used for a large spectrum of applications, and which has shown a better performance than JEFF-3.2 library [2]. Previous work carried out by NEA Data Bank on checking, processing and verification of earlier JEFF-3.3 beta releases has been presented in past JEFF meetings [3,4]. In this paper, the efforts of NEA Data Bank focused on the latest beta JEFF-3.3T4 release are presented. A review of NEA tools and databases is described in Section 2.

In Section 3, we have performed a comparison of relative standard deviation and correlation matrix with major covariance nuclear data libraries such as ENDF/B-VII.1 [5], JENDL-4.0u1 [6], SCALE6.2 [7] and the recent one CIELO1(ENDF/B-VIII.0.β5) [8]. This information gives a good indication of the current status of JEFF-3.3T4 covariances. A thorough review of the current covariance data files associated with the latest versions of the JENDL-4.0 updated files (JENDL-4.0u) and ENDF/B-VII.1 evaluated data files can be seen in reference [9].

Checking and processing issues are remarked in Section 4. After some checking tests of ENDF6 format (e.g. consistency between MF2 and MF32, energy ranges, etc.) and mathematical verification (e.g. positive definite matrix, abnormal values, etc.) few problems in raw covariances were noted. The complete set of JEFF-3.3T4 covariances (MF31, MF32/MF33, MF34 and MF35) are processed using the code NJOY2012.99 [10]; formatting and processing issues will be discussed in the paper.

The performance of JEFF-3.3T4 covariance library in criticality and safety analysis is outlined in Section 5. Nuclear data sensitivity tool (NDaST) [11] is able to propagate the covariance of nuclear data in 4501 ICSBEP benchmarks allowing to address this question in different fissile materials and neutron spectrum. This work is extended to the whole nuclear data library with especial emphasis on the four major actinides, ^{233}U, ^{235}U, ^{238}U, and ^{239}Pu. Finally, a summary of the criticality uncertainty results is given in Tables 1–4, showing the impact and differences of current covariance nuclear data evaluations.

2 NEA tools and databases

The processing and verification of nuclear data covariances have been performed with the NEA tools and databases. These tools and databases are extensively used by the nuclear data community being an essential part of the Nuclear Data Services delivered by the NEA. Hereafter, a brief summary of these tools is presented emphasising the main features on nuclear data covariances:

– The java-based nuclear information software (JANIS) [12] software developed by the NEA Data Bank is used to facilitate the visualisation and manipulation of nuclear data, giving access to evaluated nuclear data libraries, such as ENDF, JEFF, JENDL, TENDL, etc. JANIS is able to read different covariance formats: ENDF, COVERX, ERRORR and BOXER.

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Table 1. Impact of different ^{235}U nuclear data covariances in ICSBEP suite averaged for fissile material and spectrum.

	Fiss. mat.	HEU				IEU				LEU		
	Spect.	Fast	Inter.	Mix.	Therm.	Fast	Inter.	Mix.	Therm.	Fast	Mix.	Therm.
	Benchm.#	463	21	78	802	57	8	8	142	1	5	1512
	Exp. unc.	210	343	419	468	177	203	311	511	270	348	259
E-VIII.0b5	Summed	1012	1440	1100	756	934	1277	1168	753	1001	952	633
	XSs	778	601	504	285	724	574	357	311	724	572	290
	Nubar	631	1288	959	651	570	1124	1096	618	689	756	550
	PFNS	73	151	163	219	130	111	165	285	59	51	102
J-3.3T4	Summed	1190	1257	946	1043	1407	1313	883	1188	1084	916	720
	XSs	1036	1053	676	330	1158	1099	539	339	903	708	328
	Nubar	514	544	538	560	444	496	529	557	505	501	535
	PFNS	236	347	347	755	654	435	433	987	323	290	313
E-VII.1	Summed	1345	2032	1277	979	1498	1786	917	1086	1261	1025	752
	XSs	1200	1877	1077	232	1325	1606	594	256	1116	861	237
	Nubar	543	598	548	660	480	548	552	663	532	509	647
	PFNS	217	342	356	624	490	351	398	813	248	216	273
J-4.0u1	Summed	679	680	587	667	602	584	498	782	523	427	444
	XSs	614	576	459	219	403	456	294	240	444	357	232
	Nubar	243	182	177	289	204	174	197	290	222	183	283
	PFNS	134	291	303	523	381	284	336	682	164	146	228
S-6.2rev8	Summed	1189	1917	1145	786	1408	1683	765	918	1136	888	519
	XSs	1167	1859	1063	230	1323	1593	586	255	1112	856	236
	Nubar	89	146	164	367	77	143	250	366	80	121	357
	PFNS	192	337	352	611	463	337	392	797	215	198	267

– The nuclear data evaluation cycle (NDEC) [13] is used to process the JEFF-3.3T4 and ENDF/B-VIII.0β5 files. At the end of the processing NDEC produces two files, one HENDF and one BOXER. These files are then uploaded into JANIS database using the "Import Wizard" tool to create a new database. JANIS can also import directly covariance evaluations, such as SCALE-6.2 in COVERX format. For a comparison with other evaluations (e.g. ENDF/B-VII.1 and JENDL-4.0u) the NEA database is used. This NEA database provides covariances in ENDF and BOXER format for many libraries, although some important covariances are missed, such as neutron multiplicity data (nubar) and prompt fission neutron spectrum (PFNS or Chi). In this work, we have processed nubar and PFNS for ENDF/B-VII.1 and JENDL-4.0u adding the processed covariances to NEA database.
– The 2016 database for the international criticality safety benchmark evaluation project (DICE) contains 567 evaluations representing 4874 critical, near-critical, or subcritical configurations into a standardised format that allows criticality safety analysis. This database is easily used to validate calculation tools and perform benchmarking to assess the performance of evaluated nuclear data libraries. DICE provides access to sensitivity coefficients (percent changes of k-effective due to elementary change of basic nuclear data) for the major nuclides and nuclear processes in a 30-group and 238-group energy structure for 4501 experimental configurations.
– The NDaST is a Java based software, designed to perform calculations on nuclear data sensitivity files for benchmark cases. Here, NDaST is used for the calculation of the k_{eff} uncertainty due to evaluated nuclear covariance data. This allows simple and fast analysis for nuclear data evaluators to test the impact of nuclear data covariances across the 4501 ICSBEP benchmarks with sensitivities in DICE. This tool is able to predict the impact of different evaluated covariances of individual nuclides and cross-sections (e.g., elastic, inelastic, fission, capture, their cross-correlations, etc.), nubar and PFNS.

In order to more easily facilitate the input of covariances to NDaST, an automated link has been introduced to the JANIS nuclear data viewing software. From a search dialogue within the "Covariances" panel of NDaST, the user may search their public/private JANIS covariance databases for a given nuclide and reaction combination. Selection of covariance format BOXER, ENDF or COVERX returned from this search allows users to quickly calculate the propagated nuclear data uncertainty.

Table 2. Impact of different ^{238}U nuclear data covariances in ICSBEP suite averaged for fissile material and spectrum.

	Fiss. mat.	HEU				IEU				LEU		
	Spect.	Fast	Inter.	Mix.	Therm.	Fast	Inter.	Mix.	Therm.	Fast	Mix.	Therm.
	Benchm.#	463	21	78	802	57	8	8	142	1	5	1512
	Exp. unc.	210	343	419	468	177	203	311	511	270	348	259
E-VIII.0b5	Summed	49	38	12	13	428	369	154	92	124	227	291
	XSs	45	37	10	13	366	342	143	91	116	215	285
	Nubar	17	7	6	0	194	126	55	9	42	73	57
	PFNS	6	2	1	0	101	38	15	5	8	11	9
J-3.3T4	Summed	108	77	30	6	697	444	270	73	235	255	240
	XSs	107	77	29	6	658	428	265	73	232	247	235
	Nubar	14	6	5	0	154	100	44	7	33	57	45
	PFNS	8	3	2	0	153	56	20	7	11	17	13
E-VII.1	Summed	79	78	41	9	781	457	393	119	194	218	335
	XSs	74	77	40	9	668	415	388	118	188	203	329
	Nubar	17	7	6	0	189	123	54	9	41	71	55
	PFNS	17	5	3	1	319	117	39	14	25	36	26
J-4.0u1	Summed	78	64	24	7	636	394	238	85	179	211	272
	XSs	77	64	24	7	621	387	236	84	177	208	270
	Nubar	9	4	3	0	97	64	28	4	21	36	28
	PFNS	5	2	1	0	96	36	17	5	6	10	10
S-6.2rev8	Summed	69	72	40	7	748	442	386	112	182	204	327
	XSs	64	71	39	7	653	405	380	111	176	188	321
	Nubar	17	7	6	0	188	122	54	9	40	71	55
	PFNS	14	5	3	0	260	94	37	13	19	29	24

3 Nuclear data covariances

In a recent publication [9] referred as "*Comments on covariance data of JENDL-4.0 and ENDF/B-VII.1*", the latest versions of the JENDL/4.0u and ENDF/B-VII.1 covariance data have been analysed. This report concluded that those evaluation of the covariance data had not yet matured or converged on the satisfactory level in their applications. In this section, we provide a comparison of nuclear data uncertainties (relative standard deviation (RSD) in %) for CIELO files (CIELO-1=ENDF/B-VIII and CIELO-2=JEFF-3.3) and the latest JENDL-4.0 and ENDF/B-VII.1 evaluations. In addition, SCALE-6.2rev8 covariance has been also included in this analysis.

- ENDF/B-VIII.0β5(CIELO-1). The Beta-5 version of ENDF/B-VIII.0 files includes complete covariance matrices of the cross-sections, nubar, mubar and PFNS (at different energies, thermal, fast and high). The CIELO project is coordinated by the Nuclear Energy Agency/Working Party on Evaluation Cooperation (NEA/WPEC) Subgroup 40 since 2013. CIELO-1 cross-section data have been adopted by the ENDF project (https://www-nds.iaea.org/CIELO/).
- JEFF-3.3T4 (CIELO-2). It is the latest test JEF-3.3 neutron library produced via an international collaboration of Data Bank participating countries under the auspices of the NEA Data Bank. The efforts of JEFF in ^{235}U, ^{238}U and ^{239}Pu are also part of the collaboration in CIELO project. These files are the CIELO-2 set of cross-section data [1].
- SCALE-6.2. The latest SCALE-6.2.rev8 library released in 2017 which contains covariance data for 402 materials is based on ENDF/B-VII.1 and SCALE-6.1. This library includes some important changes of ENDF/B-VII.1 data such as nubar ^{239}Pu and ^{235}U. The covariance library is given in 56 and 252 group energy structure in COVERX binary format. COGNAC utility code is used to convert COVERX files between binary and ASCII (https://www.ornl.gov/scale).
- ENDF/B-VII.1 released in 2011 is largely aimed at incorporating covariance associated with a large number of nuclei and reactions, 190 materials (184 basically complete). The library is performed either using low-fidelity techniques or more robust methods relying on both experimental and model calculations; the three major actinides are evaluated with high fidelity (http://www.nndc.bnl.gov/endf/b7.1/).
- JENDL-4.0 released in 2005 provides the data for 79 actinides. After 2005, JENDL-4.0 updated files (JENDL-4.0u) are available for nuclides whose nuclear data are

Table 3. Impact of different ^{239}Pu nuclear data covariances in ICSBEP suite averaged for fissile material and spectrum.

	Fiss. mat.	PU			
	Spect.	Fast	Inter.	Mixed	Therm.
	Benchm.#	152	4	9	601
	Exp. unc.	368	505	606	371
ENDF/B-VIII.0b5	Summed	893	1550	1108	1157
	XSs	856	1538	1047	1059
	Nubar	214	146	232	333
	PFNS	120	85	275	259
JEFF-3.3T4	Summed	572	1555	1050	967
	XSs	240	1451	749	520
	Nubar	412	462	446	463
	PFNS	287	182	580	558
ENDF/B-VII.1	Summed	438	577	475	608
	XSs	409	561	368	493
	Nubar	76	93	117	166
	PFNS	120	85	276	260
JENDL-4.0u1	Summed	527	513	563	689
	XSs	448	473	348	493
	Nubar	189	123	82	78
	PFNS	182	131	434	404
SCALE-6.2rev8	Summed	343	572	465	605
	XSs	305	556	357	489
	Nubar	76	92	118	176
	PFNS	114	85	273	256

partly revised from important and/or trivial error(s) (http://wwwndc.jaea.go.jp/jendl/j40/update/).

Each of the following figures shows the RSD in % of a certain reaction cross-section. JEFF-3.3T4 and ENDF/B-VIII.0β5 have been processed with the code NJOY2012.99 in BOXER format in 238 energy groups. ENDF/B-VII.1 and JENDL-4.0u covariances are taken directly from NEA database in BOXER section which nubar and PFNS data are processed with NJOY2012.99 for this work. The SCALE-6.2 covariance file in 56 energy groups has been imported into a new JANIS database.

Figures 1–3 show the most important nuclide reactions that contribute to k_{eff} uncertainty. Five different evaluations are shown in each figure.

4 Checking and processing

The latest beta release JEFF-3.3 neutron library, JEFF-3.3T4, contains 562 files, of which 447 files including covariances. The complete set of covariances is described as follows, MF31: 50 files, MF32/MF33: 446 files, MF34: 359 files, MF35: 35 files and MF40: 286 files. For the three major actinides, ^{235}U, ^{238}U and ^{239}Pu, their covariances are evaluated using microscopic data and nuclear models. There are three nuclear data exceptions with reduced uncertainties based on the adjustment to criticality benchmarks in the fast energy region, ^{235}U(nubar) and ^{239}Pu(n,fission) and (nubar). For the ^{233}U, neither PFNS covariances nor total nubar (only prompt and delayed) are given in the library.

Firstly, the pre-checking of ENDF6 format has shown some inconsistencies between MF2 and MF32 in 40 files. The processing is performed with NJOY2012.99. Only 2 files with problems were found: ^{39}Ar which one of the l-state in MF32 mismatch the value given in MF2; and ^{9}Be a cause of the problem in NJOY2012.99 to process MT values in the 875–890 range. Both problems were solved during this work [14].

NJOY2012.99 is used to generate four different BOXER files for MF31, MF32/33, MF34 and MF35. These files can be merged into a unique BOXER file to be added into the JANIS database. The 238 energy-group is selected as the energy structure to generate covariances, because this energy structure is the most common energy structure of the k_{eff} sensitivity profiles in DICE. As an example of the use of NJOY2012.99 to process covariance of PFNS, Figure 4 shows the input to produce covariance

Table 4. Impact of different ^{233}U nuclear data covariances in ICSBEP suite averaged for fissile material and spectrum.

	Fiss. mat.	^{233}U			
	Spect.	Fast	Inter.	Mixed	Therm.
	Benchm.#	8	29	8	194
	Exp. unc.	156	662	590	548
ENDF/B-VIII.0b5	Summed	810	1154	1175	1157
	XSs	643	310	323	565
	Nubar	478	496	500	509
	PFNS	106	994	1013	814
JEFF-3.3T4	Summed	763	474	461	496
	XSs	733	353	293	202
	Nubar	210	314	356	451
	PFNS	–	–	–	–
ENDF/B-VII.1	Summed	763	474	461	496
	XSs	733	353	293	202
	Nubar	210	314	356	451
	PFNS	–	–	–	–
JENDL-4.0u1	Summed	810	1143	1154	991
	XSs	643	264	235	187
	Nubar	478	496	500	509
	PFNS	106	994	1013	814
SCALE-6.2rev8	Summed	743	1083	1094	951
	XSs	705	342	287	201
	Nubar	212	323	363	453
	PFNS	97	974	991	794

boxer files for ^{239}Pu/JEFF-3.3T4. Figure 5 is an example of different RSD in % of PFNS for ^{239}Pu/JEFF-3.3T4 as a function of different mean incident neutron fission energy.

A special NJOY input is needed to process cross-section covariance in JEFF-3.3T4 files with only MF32 section (e.g. ^{35}Cl, ^{37}Cl, ^{231}Pa, ^{233}Pa and ^{241}Am). See Figure 6 for ^{231}Pa's NJOY input.

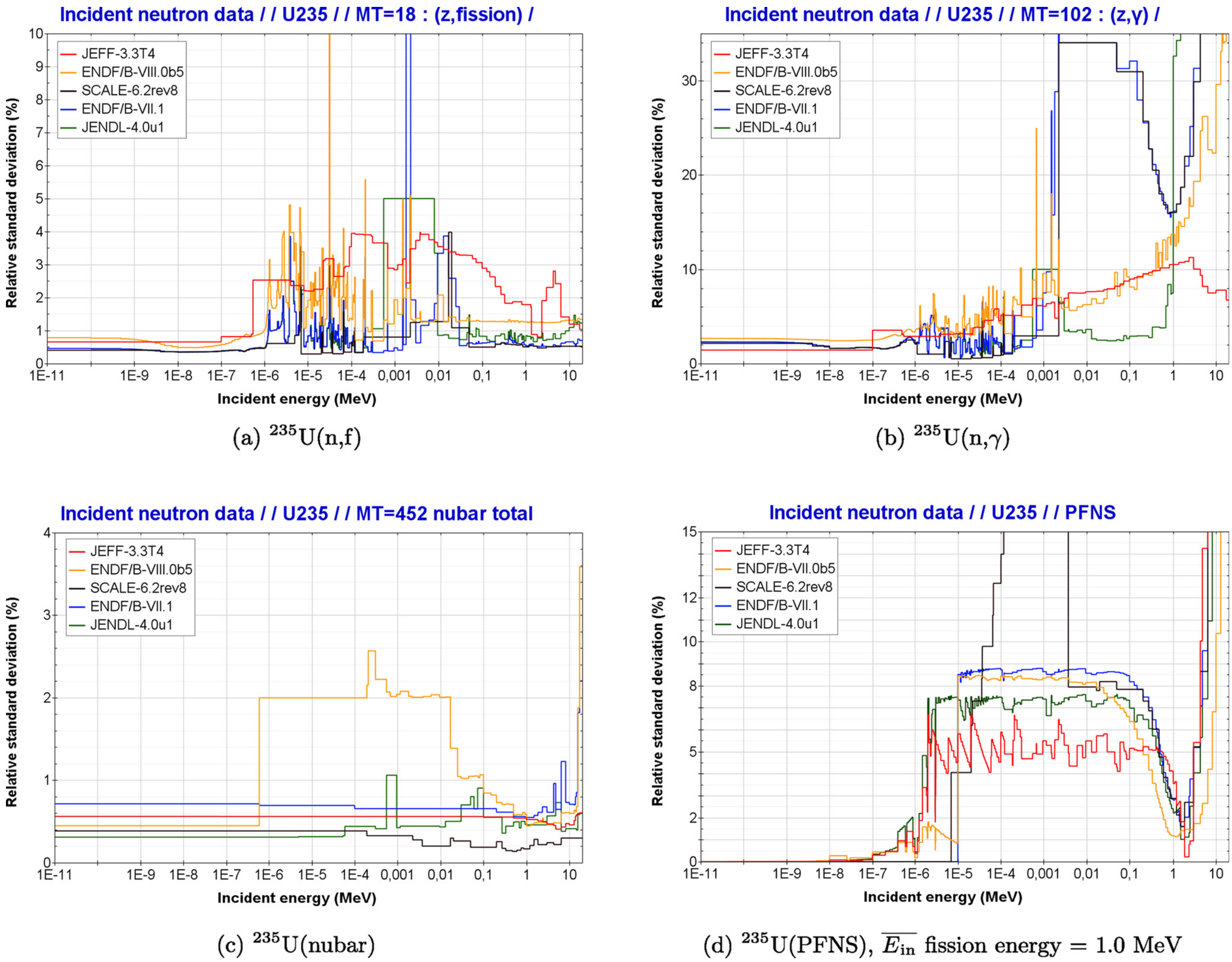
LAMDA code [15] is applied to the full BOXER files generated to identify non-positive definite matrices, only 30 matrices with negative eigenvalues were found, of a total number of 6931. Large uncertainties values are also checked to identify potential problems either in the evaluation or in the processing step. None of these problems were found in matrices relevant for criticality uncertainty assessment.

5 Verification of nuclear data covariances

The goal of this section is to assess the completeness of covariance files and the performance of these nuclear data uncertainties in a safety and criticality assessment. NDaST tool is bringing together the existing capabilities of both DICE and JANIS, to quickly propagate the impact of nuclear data covariances to criticality benchmarks. Generally speaking, the comparison of propagated nuclear data uncertainties against evaluated experimental uncertainties will give a good idea of the performance of the nuclear data. In addition, the comparison of propagated nuclear data uncertainties among nuclear data evaluations will permit to assess the completeness, disagreements and potential deficiencies of nuclear data covariances.

In order to more easily facilitate the analysis, NDaST shows graphically in a plot the k_{eff} C/E values (in red), experimental uncertainties (in blue) and the propagated nuclear data uncertainties (in green). Figure 7 shows these values for the selection of FAST/Pu benchmarks in the Mosteller suite [2] using the JEFF-3.3T4 library. In this Figure 7, the nuclear data uncertainties only take into account the ^{239}Pu nuclear data uncertainty.

NDaST predicts the propagated uncertainty for a given nuclide and reaction combination. For the FAST/Pu benchmarks of Figure 7, in JEFF-3.3T4 the most important contributors to the k_{eff} uncertainty are fission (~300 pcm), nubar (~400 pcm) and PFNS (~360 pcm). The contribution for elastic and inelastic cross-section uncertainties are smaller, ~ 60 and ~100 pcm, respectively.



(a) ^{235}U(n,f)

(b) ^{235}U(n,γ)

(c) ^{235}U(nubar)

(d) ^{235}U(PFNS), $\overline{E_{\text{in}}}$ fission energy = 1.0 MeV

Fig. 1. Relative standard deviation (%) for ^{235}U.

However, other nuclear data evaluations returned highest averaged values of uncertainty due to elastic and inelastic cross-sections, ENDF/B-VIII.0β5 (~300 and ~540 pcm), ENDF/B-VII.1 (~290 and ~540 pcm) and JENDL-4.0u1 (~125 and ~170 pcm).

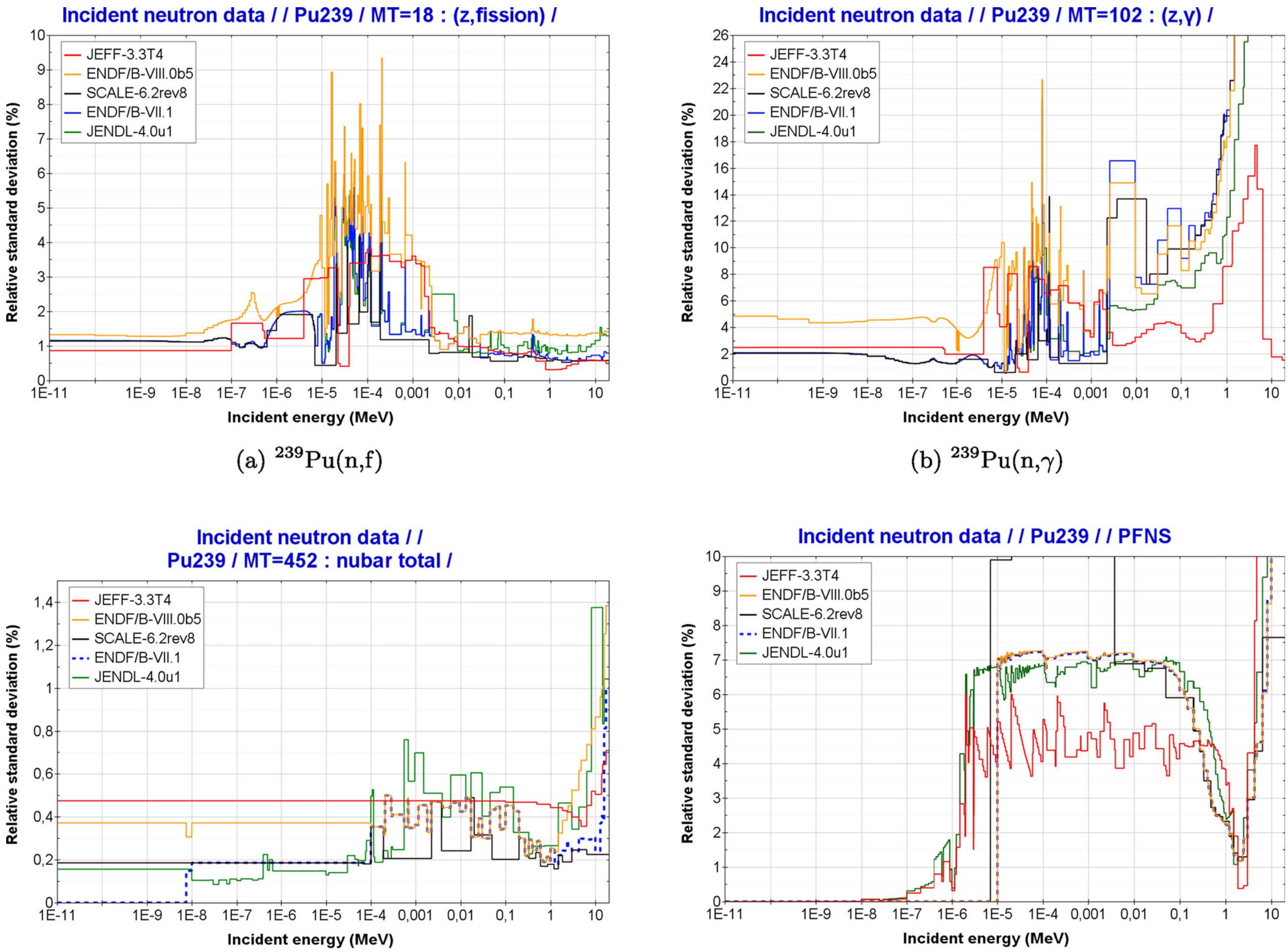
Besides ^{239}Pu in FAST/Pu cases, other nuclides contribute to increase the k_{eff} uncertainty. As an example, the JEFF-3.3T4 top contributors in PMF9-1 benchmark are ^{27}Al(703 pcm), ^{239}Pu(532 pcm) and ^{240}Pu(182 pcm). For PMF8-1 benchmark are ^{239}Pu(609 pcm), ^{232}Th (296 pcm) and ^{240}Pu(180 pcm). For the Mosteller suite, we have identified the most important contributor by isotope/element and by benchmark case for the JEFF-3.3T4 nuclear data evaluation. The following is a list of these results by element: ^{16}O in HSI1-1: 367 pcm, ^{27}Al in PMF9-1: 703 pcm, Fe in PMF26-1: 439 pcm, Cu in HMI6-4: 506 pcm, W in PMF5-1: 605 pcm, Zr in UCT1-3: 234 pcm, ^{233}U in UMF1-1: 884 pcm, ^{23}5U in HMI6-4-1: 1564 pcm, ^{238}U in IMF7-1: 970 pcm, ^{239}Pu in PCI1-1: 2097 pcm, ^{240}Pu in PMF2-1: 834 pcm, ^{241}Pu in PST18-9: 472 pcm, 1H in UST8-1: 1302 pcm and ^{2}H in HSI1-1: 2958 pcm.

Tables 1–4 give the averaged uncertainty (in pcm) in k_{eff} calculated with NDaST in the ICSBEP benchmark suite for each type of fissile material and neutron spectrum. Nuclear data covariances for the four major isotopes (^{233}U, ^{235}U, ^{238}U and ^{239}Pu) are propagated with DICE sensitivities and then averaged for the number of bechmarks of each type of fissile material. PFNS covariances are assumed at 1 MeV incident neutron fission energy.

The averaged experimental k_{eff} value is shown after the number of Benchmarks for comparison.

The following is a brief summary of the findings and conclusions based on the results shown in Tables 1–4:

– SCALE-6.2 shows lower uncertainties in Pu cases because the low value of nubar around 0.2% (similar to ENDF/B-VII.1). High uncertainties are found in HEU



(a) ^{239}Pu(n,f)

(b) ^{239}Pu(n,γ)

(c) ^{239}Pu(nubar)

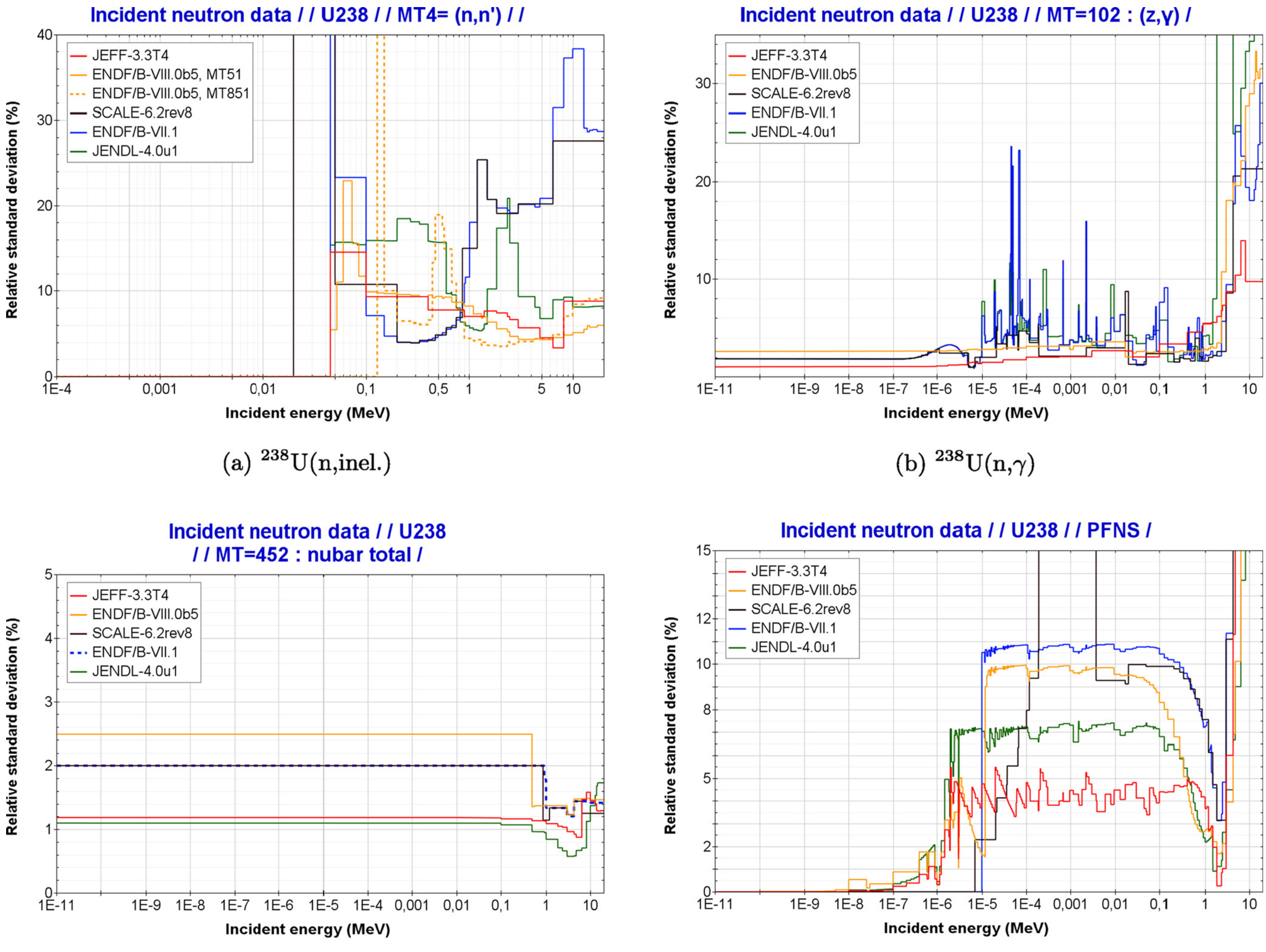
(d) ^{239}Pu(PFNS), $\overline{E_{\text{in}}}$ fission energy = 1.0 MeV

Fig. 2. Relative standard deviation (%) for ^{239}Pu.

and IEU cases because the high ^{235}U(n,γ) uncertainty in kev-MeV energy range. Also to be remarked the high contribution to k_{eff} uncertainty of ^{235}U(PFNS) and ^{233}U (PFNS).

– In JEFF-3.3T4, the lack of uncertainty in ^{233}U/PFNS gives the lower values for ^{233}U cases (=ENDF/B-VII.1). The high uncertainty for ^{235}U(n,fission) in keV-MeV provokes the largest uncertainties in HEU-IEU for FAST–INTERM neutron spectrum, ~1100–1400 pcm. For PU case, the intermediate spectrum shows the highest uncertainty ~1500 pcm, as a consequence of the high uncertainty in ^{239}Pu (n,fission) and nubar.
– JENDL-4.0u shows the higher uncertainties in ^{233}U cases because the higher uncertainties in ^{233}U nubar and PFNS. For PU-thermal and mixed neutron spectrum cases, it can be seen the impact of large uncertainty in JENDL-4.0u ^{239}Pu(PFNS).
– For ENDF/B-VIII.0β5, it is very significant the large uncertainty in ^{235}U nubar, around 1% in the keV energy range which produces ~1100 pcm k_{eff} uncertainty in the HEU and IEU/intermediate neutron spectrum cases. A comparison with ENDF/B-VII.1 in Table 1 shows lower uncertainty contribution for ^{235}U PFNS and cross-sections. In addition, the uncertainty ^{238}U(n,γ) is significantly smaller in CIELO-1 giving lower uncertainty in LEU and IEU cases. ^{239}Pu fission and nubar uncertainties are increased in ENDF/B-VIII.0β5, it has a large impact in PU/INTER benchmarks. The ^{233}U uncertainties for nubar and PFNS are taken from JENDL-4.0u.

Tables 1–4 show large values of the nuclear data uncertainty in comparison with the experimental uncertainty. In general, much more accurate criticality calculations are predicted with the evaluated librarires to match low |C-E| values. For instance, JEFF-3.3T4, for a set of 2233 ICSBEP benchmarks, it gives around 50% of benchmarks within 1σ experimental uncertainty and 90% of benchmarks within 1σ nuclear data uncertainty. It shows the too-wide range of nuclear data covariances.



(a) ^{238}U(n,inel.)

(b) ^{238}U(n,γ)

(c) ^{238}U(nubar)

(d) ^{238}U(PFNS), $\overline{E_{\text{in}}}$ fission energy = 1.0 MeV

Fig. 3. Relative standard deviation (%) for ^{238}U.

6 Conclusion

JEFF-3.3T4 contains 447 files with covariance of average number of neutrons per fission (MF31), resonance parameters (MF32), cross-sections (MF33), angular distributions of elastic scattering (MF34), prompt fission spectrum (MF35) and radionuclide production (MF40). These covariances have been checked (e.g. ENDF6 format) and processed with NJOY2012.99. The verification of these covariances have been performed with mathematical (e.g. identifying negative eigenvalues) and physical (e.g. comparison with other evaluations) procedures, as well as quantifying the impact of these covariances in criticality uncertainty analysis.

Future developments in DICE/NDaST will permit to use covariance data for angular distributions. Other important feature is to extend the analysis to shielding benchmarks which will permit to quantify the impact of these covariances in other applications.

Recently, two new projects coordinated by the NEA-WPEC have been initiated: (i) Subgroup 46 on “Efficient and Effective Use of Integral Experiments for Nuclear Data Validation” [16] to define the methodology for verifying the physical properties of nuclear data covariances based on Adjustment methodologies; (ii) Subgroup 44 on “Investigation of Covariance Data in General Purpose Nuclear Data Libraries” [17] to provide guidance to the international community on methods for systematic and consistent evaluation of covariance data for the whole energy range. This underlines that defining credible nuclear data uncertainties remains still a challenging problem for the nuclear data community [18].

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groupr / Generate multigroup cross section data
21 24 0 31/
9437 1 0 2 0 1 1 1 /
'94-Pu-239 GENDF-33g jeff33t4, NEA 2017-07-27'/
300.0
1.E10
238 /
    1.000E-05, 1.000E-04, 5.000E-04, 7.500E-04, 1.000E-03,
    ...
    1.455E+07, 1.568E+07, 1.733E+07, 2.000E+07/
 3/
3 452 nubar_t/
3 455 nubar_d/
3 456 nubar_p/
5 455 nubar_spc/
5  18 nubar_spc/
0/
0/
errorr
21 0 31 77 /
9437 1 2 1 1 /
1  300.0 / Just only one temperature
0 35 1 1 -1 1.0E+5/
238 /
    1.000E-05, 1.000E-04, 5.000E-04, 7.500E-04, 1.000E-03,
    ...
    1.455E+07, 1.568E+07, 1.733E+07, 2.000E+07/
covr
 77 78 /
 3 1
' jeff33t4 ' /
' in BOXER format ' /
9437 0 0 0 /
stop
```

Fig. 4. An example of NJOY input to process MF35/PFNS covariance.

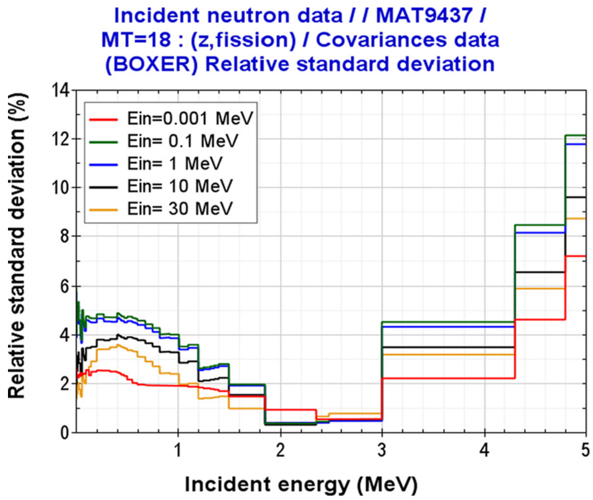

Fig. 5. RSD in % of ^{239}Pu/JEFF-3.3T4 PFNS distributions as a function of mean incident neutron fission energy.

```
error
999/
21 88/
1/
2/
102/
0/
errorr
88 0 31 77 /
9131 1 2 1 1 /
1  293.6 / Just only one temperature
0 33 /
238 /
    1.000E-05, 1.000E-04, 5.000E-04, 7.500E-04, 1.000E-03,
    1.200E-03, 1.500E-03, 2.000E-03, 2.500E-03, 3.000E-03,
...
...
```

Fig. 6. NJOY input to process files with only MF32.

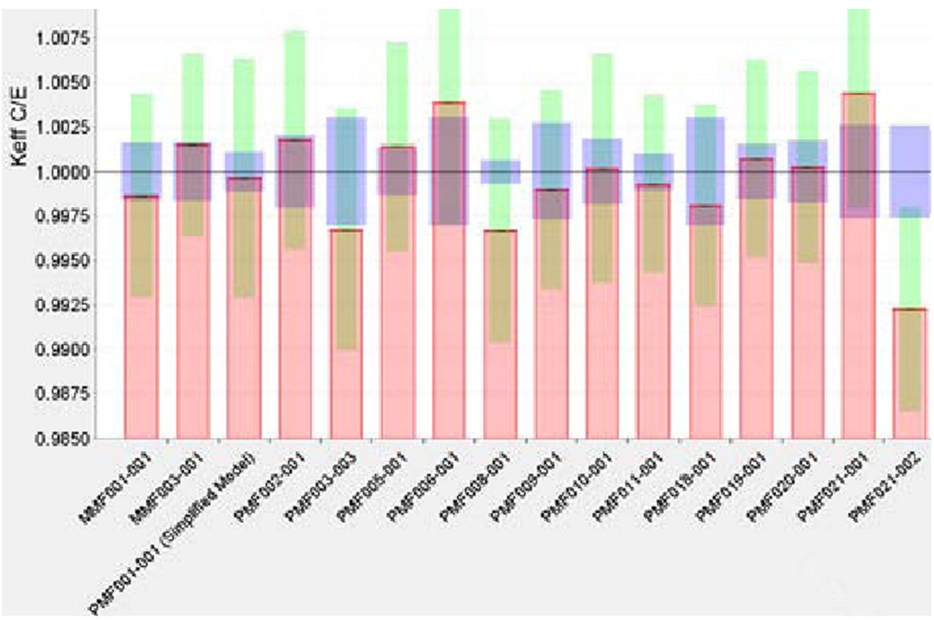

Fig. 7. NDaST output plot, k_{eff} C/E (in red), experimental (in blue) and propagated nuclear data uncertainties (in green) due to ^{239}Pu covariance of JEFF-3.3T4.

Author contribution statement

O. Cabellos and J. Dyrda conceived the present work. O. Cabellos carried out the first part of the work on checking and processing nuclear data covariance. O. Cabellos and J. Dyrda performed the verification of nuclear data uncertainties assessing the impact on keff uncertainty in the ICSBEP benchmark suite. O. Cabellos and J. Dyrda supervised the main findings of this work. N. Soppera updated JANIS and NDaST tools, new capabilities for visualization and computing were applied in this work. O. Cabellos wrote the manuscript with support from J. Dyrda and N. Soppera.

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