EPJ Web of Conferences **308**, 04002 (2024) https://doi.org/10.1051/epjconf/202430804002
ISRD 17

Measurements of ^{235}U(nth,f) Spectrum Averaged Cross Sections (SACS) in zero power reactors

Michal Košťál[1,*], *Evžen* Losa[1,2], *Tomáš* Czakoj[1], *Tomáš* Bílý[2], *Martin* Schulc[1], *Vlastimil* Juříček[1], *Jan* Šimon[1], *Martin* Mareček[1], *Jan* Uhlíř[1], *Alena* Krechlerová[1], *Stanislav* Simakov[3], *Andrej* Trkov[4], and *Roberto* Capote[5]

[1]Research Center Rez, Husinec-Rez, 250 68, 130, Czech Republic
[2]Czech Technical University, FNSPE, Prague, Czech Republic
[3]Institute for Neutron Physics and Reactor Technology, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
[4]Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia
[5]Nuclear Data Section, International Atomic Energy Agency, A-1400 Wien, Austria

Abstract. This paper deals with the measurement of Spectrum Averaged Cross Sections in two different neutron fields formed in zero power reactors. The first was Benchmark Neutron Reference Field in the LR-0 reactor, and the second field was in the center of the vertical channel touching the fuel in the VR-1 reactor. The spectrum averaged cross section differs for both cases as the spectra differ, but after normalization to ^{235}U PFNS using calculated correction, both results are in good agreement, thus confirming the spectra in both cases are similar in the 1 – 14 MeV region. A good agreement between lower threshold reactions averaged in actual reactor spectra and prompt fission neutron spectrum of ^{235}U is reported as well.

1 Introduction

The evaluation of the neutron flux using reaction rates of various dosimetry reactions is very sensitive to the used cross section. Therefore, the validation and uncertainty evaluation of employed evaluated cross sections is essential. Integral cross sections measured in standard and/or reference neutron benchmark fields are very well suited for such validation.

The neutron field at the center of the LR-0 reactor special core has been proposed and validated as a reference neutron field [1]. In this central position, an extensive set of spectrum averaged cross sections (SACS) measurements were undertaken. The LR-0 uses low enriched fuel (3.3 wt.%), thus the contribution of ^{238}U neutron induced fission neutrons may play some role. To evaluate the possible ^{238}U effect, the same measurements were undertaken in parallel at the VR-1 reactor where the larger neutron spectrum with higher energy neutrons can be reached. The VR-1 is using a significantly higher enriched fuel (19.7 wt.%) where the ^{238}U fission neutrons contribute less than 0.5 % [2] to the measured reaction rates, compared to more than 5 % in the case of the LR-0 [3]. The measurements were performed in various positions in the core to exclude possible contribution by gamma activation [4]. Such

* Corresponding author: Michal.Kostal@cvrez.cz

comparison is valid because direct spectrum measurement with stilbene scintillation spectrometry confirmed the similarity of LR-0 and VR-1 neutron spectra in the region above 2 MeV [5]. Measured SACS sets in LR-0 and VR-1 spectra are in good agreement and they agree very well with calculated SACS using the recent release IAEA IRDFF-II library. The observed good agreement guarantees the negligible impact of the ^{238}U fission neutrons on measured data in both reactors.

The developed methodology for SACS measurement in zero power reactors is innovative because the activation is realized in low flux in a dry assembly where the portion of fast neutrons is significant. The use of zero power reactors means that the fuel burn-up is negligible, so there is practically no plutonium accumulated. On the other hand, difficulties can occur with the detection of induced radioisotopes. This issue is solved by using well characterized HPGe which allows measuring of even large samples in very close geometry.

2 The Reactor Arrangements

2.1 LR-0 reactor

Part of the experiments was realized in the LR-0 reactor. It is pool type reactor with pin type fuel in a hexagonal VVER-1000 lattice. Several enrichments are available for this reactor. The irradiations were carried out in the dry central channel in the special core in the LR-0 reactor where the benchmark reference neutron field was identified [1]. Such field is defined as a permanent reproducible neutron field with well-defined neutron fluence rate and neutron energy spectrum. The neutron fluence rate and neutron spectra were determined experimentally and by calculation. Thanks to good agreement between both [6] the calculational model of the field can be understood as well validated. The field is formed by fission neutrons emitted from fuel. This source term vas validated as well [7]. Moreover, it was proven that in the region above 6 MeV the neutron spectrum in such region is indistinguishable from the ^{235}U prompt fission neutron spectrum [5]. The comparison between calculated neutron spectrum in reference field and in VR-1 is plotted in Fig. 1.

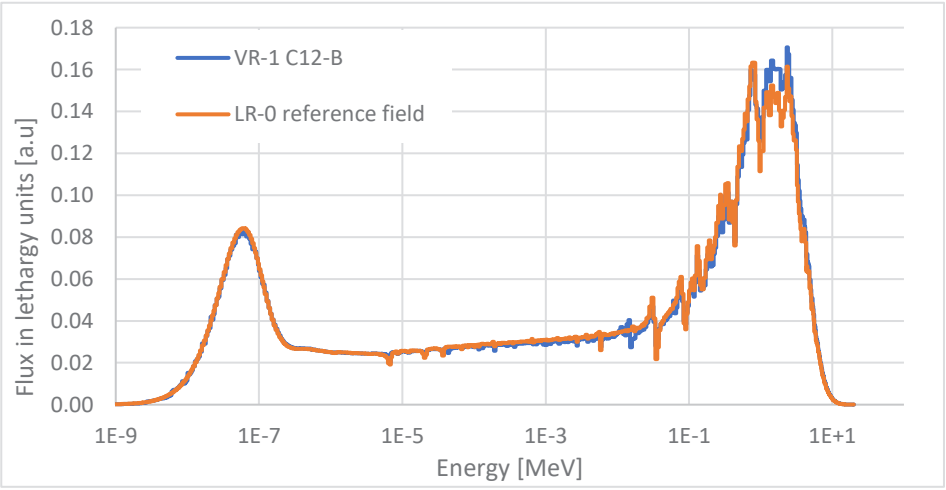

Fig. 1. Comparison of LR-0 and VR-1 neutron spectra in irradiation position.

2.2 VR-1 reactor

Other set of foils was irradiated in the C12B core of the VR-1 reactor [8]. The VR-1 reactor is located at the Department of nuclear reactors of the Czech Technical University in Prague [9] and is classified as a pool-type research reactor with nominal power of 100 W thermal and maximum power of 500 W thermal. Past experimental efforts have been devoted to the point kinetic parameters measurement [10], neutron spectrum characterization [2,11] or research in neutron radiography [12]. Thanks to the significantly higher fluxes than in the LR-0 case (~ 100×), the small foils in small volumes can be used for irradiations. Due to this irradiation geometry where the energy dependent neutron flux in monitors is identical with flux in foils, and due to well validated neutron spectra corrections to ^{235}U PFNS can be determined [8].

3 Experimental and Calculation Methods

The spectrum averaged cross sections were derived from measured Net Peak Areas (NPA) of activation products induced by studied reaction in dosimetry foils and neutron fluxes calculated in foils using well validated MCNP model. The NPAs were determined using HPGe spectrometry. The measurements confirm that the spectrum in LR-0 is undistinguishable from ^{235}U PFNS in region 6 - 14 MeV and in VR-1 in region 6 – 11 MeV.

3.1 Gamma spectrometry

The HPGe detector was used in gamma spectrometry measurements. The measured quantity was Net Peaks Areas (NPA) from activation products induced in foils during irradiation. These quantities were used for the determination of induced activity (Eq.1) and following reaction rates (Eq. 2).
The non-constant power profile during irradiation, due to control rod variation, was taken into account by evaluation with an A/A_{sat} ratio (see Eq. 3). The detector efficiency used in evaluations was determined by calculation using validated model of the HPGe detector. The appropriate Coincidence Summing Factors were determined also using the MCNP6.2 code [13]. The detector efficiency uncertainty was determined to be 1.9 % and was assessed from the difference between the experimentally determined efficiency and the efficiency determined with the HPGe model.

$$A_{\mathrm{End}} = NPA(T_{\mathrm{Meas.}}) \times \frac{\lambda}{\varepsilon \times \eta} \times \frac{1}{\left(1-e^{-\lambda.T_{\mathrm{Meas.}}}\right)} \times \frac{1}{e^{-\lambda.\Delta T}} \times \frac{1}{k_{\mathrm{CSCF}}} \quad (1)$$

$$q\left(\overline{P}\right) = A_{\mathrm{End}}/N \times \left(\frac{A(\bar{P})}{A_{Sat.}(\bar{P})}\right)^{-1} \quad (2)$$

$$\frac{A(\bar{P})}{A_{Sat.}(\bar{P})} = \sum_{i=1}^{n} \frac{P_i}{\bar{P}} \cdot \left(1 - e^{-T_i \cdot \lambda}\right) \cdot e^{-\lambda \cdot T_i^{End}} \quad (3)$$

$NPA(T_{\mathrm{Meas.}})$ measured Net Peak Area of the observed nuclei i and selected peak; $T_{\mathrm{Meas.}}$ beginning of the measurement interval; λ decay constant of selected nuclide; η efficiency of HPGe for the selected gamma line; ε gamma branching ratio of the selected peak; k_{CSCF} coincidence summing correction factor; ΔT decay time between end of irradiation and start

of HPGe measurement; $q(\overline{P})$ is reaction rate in average power $\overline{P}$; N is number of nuclei in activation foil

3.2 Simulation of neutron transport

Reactor and neutron spectra calculations were performed using the MCNP6.2 Monte Carlo code [14] and ENDF/B-VIII.0 [15] data library. The reaction rates used in the normalization of the reactor neutron emission rate were calculated from calculated neutron spectra using IRDFF-II nuclear data library [16].
In the case of LR-0, the precise model was used in simulations [17]. Thanks to the fact that the model is benchmarked, the reaction rates of monitors positioned in well-defined positions are used for the determination of the neutron scaling factor. That in fact allows to determine the neutron flux in dosimeters. For the purpose of flux monitoring, 20 foils in 12 selected positions were used. The reactions were used to cover all energy regions, namely ^{197}Au(n,g) for thermal flux, ^{181}Ta(n,g) for epithermal flux, and ^{58}Ni(n,p) for fast flux. The scaling, in the meaning of neutron emission rate, is determined by a comparison between calculated and experimentally determined reaction rates in a defined position. The used scaling factor is average from all positions. The uncertainty in this factor is determined as the mean deviation between each position scaling.
In the case of VR-1, the neutron flux in the irradiation position was calculated. Small foils were used, thus the material and geometrical corrections can be neglected, and flux in dosimetry foils is identical to flux in monitors [8]. Nickel foils and dosimetry reaction ^{58}Ni(n,p) were used for monitoring. In this approach, the thermal and epithermal regions are not covered by monitors, thus the evaluation is oriented to threshold detectors. The uncertainties of calculated quantities are not more than 0.2%, thus they play only a minor role in evaluation.
The resulting scaling factors together with flux in dosimeters are listed in Table 1.

Table 1. Quantities used for scaling determined by calculations.

	Scaling factor [n/s]	Unc.	Flux in dosimeters [$cm^{-2}\cdot s^{-1}$]	Share of neutrons with En>6 MeV in neutron spectra
LR-0	7.961E+11	2.3%	2.200E-4	7.140E-3
VR-1	4.879E+13	0.8%	6.556E-4	7.551E-3
^{235}U PFNS	-	-	-	2.566E-2

4 Results

4.1 Reaction rates

The measured NPAs in both LR-0 and VR-1 were evaluated as reaction rates (see Table 2). The reaction rates in LR-0 are significantly smaller than those measured in VR-1 which is caused by a significantly higher power level in VR-1 (~ 650 W) than in LR-0 (~ 10W). This reaction rates can be evaluated as spectrum averaged cross sections using flux in detector foils, which is derived from monitor foils. When evaluated as a spectrum average cross section, the values are nearly comparable, and the differences are reflecting differences in LR-0 and VR-1 spectra (see Fig. 2). The presented uncertainty is reflecting major uncertainty

sources (measurement uncertainty, HPGe uncertainty, uncertainty in evaluated flux used in evaluation).

Table 2. Results of measurement and evaluated SACS using flux simulations.

	Measured values of reaction rates [s^{-1}]		Evaluated SACS			
			LR-0 experiment		VR-1 experiment	
	LR-0	VR-1	Mean [b]	rel. unc.	Mean [b]	rel. unc.
^{47}Ti(n,p)	8.77E-19	1.72E-16	5.008E-3	3.4%	5.391E-3	2.9%
^{54}Fe(n,p)	3.84E-18	7.51E-16	2.191E-2	3.7%	2.346E-2	3.1%
^{92}Mo(n,p)	3.38E-19	6.36E-17	1.928E-3	3.3%	1.987E-3	3.1%
^{46}Ti(n,p)	5.22E-19	1.01E-16	2.981E-3	3.2%	3.160E-3	3.3%
^{63}Cu(n,α)	2.46E-20	5.00E-18	1.405E-4	3.7%	1.563E-4	3.3%
^{56}Fe(n,p)	5.21E-20	9.80E-18	2.974E-4	3.3%	3.063E-4	3.0%
^{48}Ti(n,p)	1.41E-20	2.77E-18	8.070E-5	3.4%	8.668E-5	3.1%
^{27}Al(n,α)	3.28E-20	6.42E-18	1.873E-4	3.8%	2.007E-4	3.0%

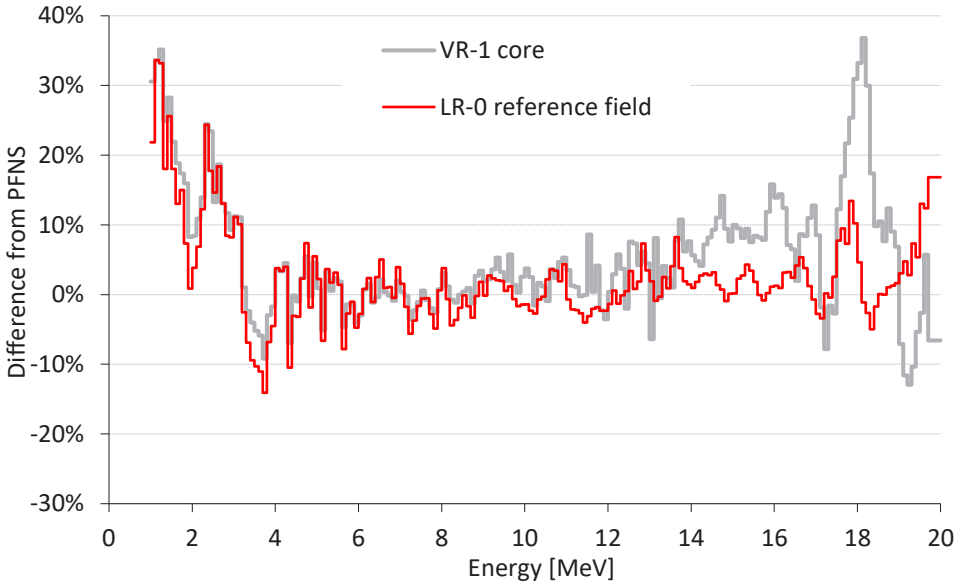

Fig. 2. Comparison of actual normalized shape of reactor spectra and ^{235}U(n_th, fiss.) PFNS.

4.2 Spectrum averaged cross sections

The spectrum averaged cross sections are unique quantities different for any reactor depending on its spectrum. To allow intercomparison it is necessary to normalize the experiment to a standard spectrum (see Table 3). The ^{235}U PFNS was defined as neutron standard [16], so it is tempting to correct the SACS averaged in reactor spectra to SACS averaged in ^{235}U PFNS. It was shown (see Fig. 2) that both spectra are undistinguishable from ^{235}U PFNS in region 6 – 14 MeV, and do not differ more than ~15-20 % in region 1.5 – 6 MeV.

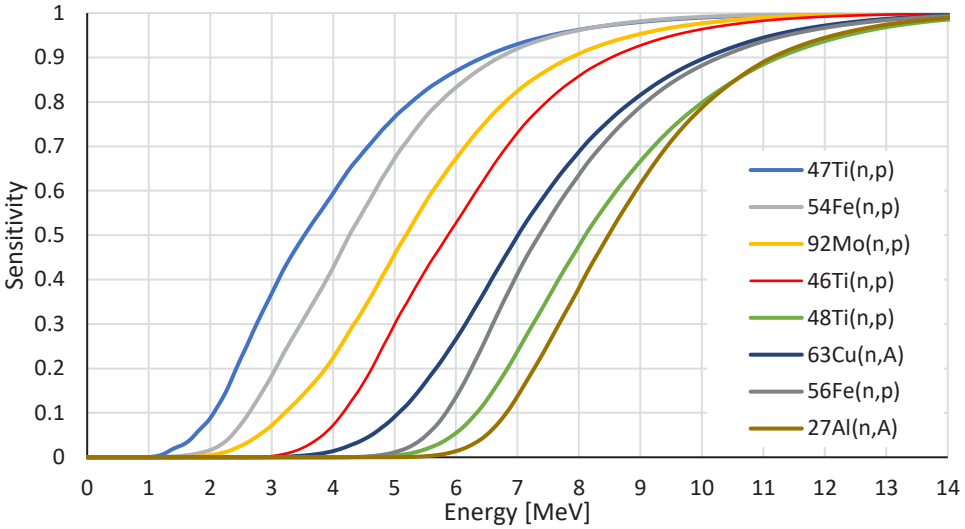

Fig. 3. Calculated sensitivities in VR-1 spectrum.

The set of measured reaction rates was selected to be sensitive in region 1 – 14 MeV (see Fig. 3), where the spectra are close to ^{235}U PFNS (see Fig.4.). It was presented that in the region above 6 MeV, the spectrum averaged cross sections can be simply evaluated as spectrum averaged cross section weighted by ^{235}U PFNS. However, due to not high differences between the uranium fission spectrum and actual reactor spectra, the corrections were applied to all studied reactions. It is worth noting that the evaluated cross sections are in good agreement with theoretical prediction. It is reflecting the fact that variation of reactor spectra has an variation character (due to oxygen effect [8]) and local increases are compensated by local decreases.

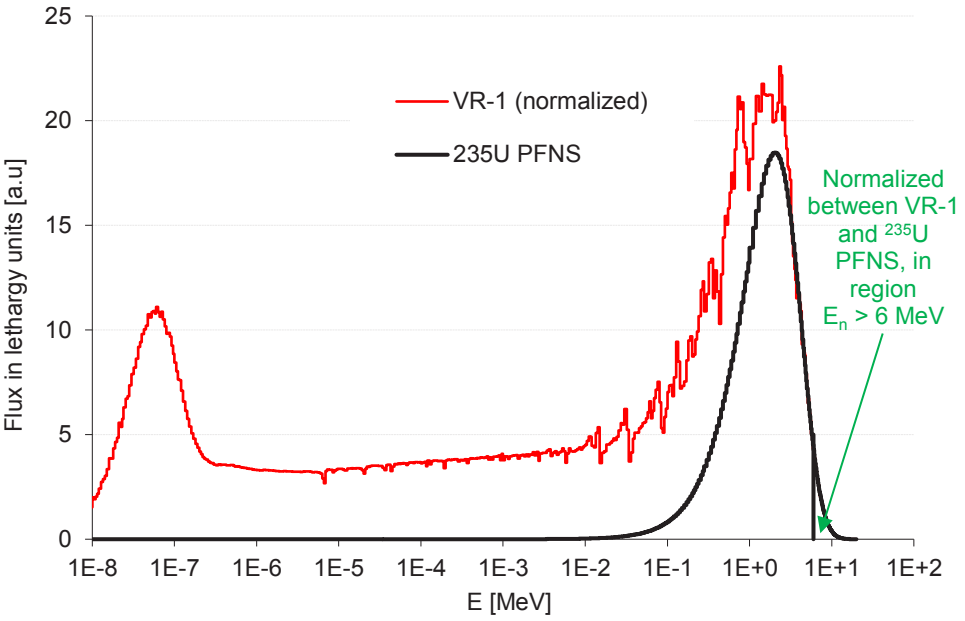

Fig. 4. Comparison between VR-1 spectrum and ^{235}U Prompt Fission Neutron Spectra.

Table 3. Evaluated SACS [mb] averaged in ^{235}U PFNS (used correction factors in Tab.2).

	LR-0	VR-1	IRDFF-II	VR-1/LR-0 - 1	Eval./Exp.-1
^{47}Ti(n,p)	18.00	18.32	17.77	1.8%	-2.2%
^{54}Fe(n,p)	78.76	79.75	76.66	1.3%	-3.3%
^{92}Mo(n,p)	6.930	6.753	6.572	-2.5%	-3.9%
^{46}Ti(n,p)	10.72	10.74	11.12	0.2%	3.6%
^{63}Cu(n,α)	0.505	0.531	0.515	5.2%	-0.7%
^{56}Fe(n,p)	1.069	1.041	1.058	-2.6%	0.3%
^{48}Ti(n,p)	0.290	0.295	0.293	1.6%	0.4%
^{27}Al(n,α)	0.673	0.682	0.687	1.3%	1.4%

5 Conclusions

The spectrum averaged cross sections were evaluated for both LR-0 and VR-1 reactors. When corrected to ^{235}U PFNS, both LR-0 and VR-1 results are consistent, with differences comparable or smaller than uncertainty. It's worth noting, the average value of experimental SACS averaged in ^{235}U PFNS is in good agreement with theoretical values in IRDFF-II. Slight underprediction of experimental values of SACS is reported regarding to tabulated ones in low energy threshold reactions like ^{47}Ti(n,p). This is consistent with the overprediction of actual neutron spectra and ^{235}U PFNS. However, the magnitude of discrepancy is lower than 5 %, thus it can be stated, that in reaction rates measurement the reactor spectra doesn't differ from ^{235}U PFNS by more than 5 %.

The presented work has been realized within Institutional Support by the Ministry of Industry and Trade and with the use of the infrastructure Reactors LVR-15 and LR-0, which is financially supported by the Ministry of Education, Youth and Sports – project LM 2023041.

References

1. M. Košťál, M. Schulc, E. Losa et al., A reference neutron field for measurement of spectrum averaged cross sections, Ann. of Nucl. En., Vol. 140, (2020), 107119
2. M. Kostal, E. Losa, Z. Matej et al., Characterization of mixed N/G beam of the VR-1 reactor, Ann. of Nucl. En., 122, (2018), 69–78
3. M. Košťál, Z. Matěj, F. Cvachovec et al., Measurement and calculation of fast neutron and gamma spectra in well defined cores in LR-0 reactor, Appl. Rad and Isot. 120, (2017), pp. 45–50
4. M. Kostal, E. Losa, S. Simakov et al., Impact of reactor neutron spectrum on measured spectrum averaged cross sections, Ann. of Nucl. En., 179 (2022), 109418
5. M. Košťál, Z. Matěj, E. Losa et al., On similarity of various reactor spectra and 235U prompt fission neutron spectrum, Appl. Rad. and Isot., Vol. 135 (2018), pp. 83–91
6. M. Koštál, M. Schulc, J. Simon et al., 2018b. ''Measurement of various monitors reaction rate in a special core at LR-0 reactor, Ann. Nucl. En. 112, 759–768
7. M. Košťál, E. Losa, T. Czakoj et al., The effect of heavy reflector on neutronic parameters of core, Ann. of Nucl. En., 168, (2022), 108898
8. M. Kostal, E. Losa, M. Schulc et al., Validation of IRDFF-II library in VR-1 reactor field using thin targets, Ann. of Nucl. Energy 158, (2021), 108268

9. L. Frybortova, J. Rataj, L. Sklenka, J. Frybort, F. Fejt and O. Novak, "The Training Reactor VR-1 - 30 Years of Operation," 2020 21st International Scientific Conference on Electric Power Engineering (EPE), Prague, Czech Republic, 2020, pp. 1-7
10. T. Bily, J. Rataj, O. Huml, O. Chvala, Effect of kinetics parameters on transients calculations in external source driven subcritical VR-1 reactor, Annals of Nuclear Energy, Vol. 123, 2019, Pp. 97-109
11. E. Losa, M. Košťál, M. Štefánik, J. Šimon, T. Czakoj, Z. Matěj, F. Cvachovec, F. Mravec, J. Rataj, and Ľ. Sklenka, (November 16, 2020). "Validation of the Fast Neutron Field in the Radial Channel of the VR-1 Reactor." ASME. *ASME J of Nuclear Rad Sci*. April 2021; 7(2): 021503
12. J. Matouskova, B. Schillinger, L. Sklenka, New Neutron Imaging Facility NIFFLER at Very Low Power Reactor VR-1. *J. Imaging* **2023**, *9*, 15
13. E. Tomarchio, S.Rizzo, Coincidence-summing correction equations in gamma-ray spectrometry with p-type HPGe detectors, Radiation Physics and Chemistry, Vol. 80 (2011), pp. 318-323
14. Goorley et al., 2012 T. Goorley, et al., "Initial MCNP6 Release Overview", NuclearTechnology, 180, pp 298-315 (Dec 2012)
15. D. A. Brown, M. B. Chadwick, R. Capote, et al., ENDF/B-VIII.0: the 8th major release of the nuclear reaction data library with CIELO-project cross sections, new standards and thermal scattering data, Nucl. Data Sheets, 148 (2018), pp. 1-142
16. A. Trkov, P.J. Griffin, S.P. Simakov et al., IRDFF-II: A New Neutron Metrology Library, Nuclear Data Sheets, Vol. 163, 2020, pp. 1–108
17. M. Kostal, V. Rypar, E. Losa et al., LR(0)-FUND-RESR-001 CRIT-RRATE, VVER-1000 PHYSICS EXPERIMENTS HEXAGONAL LATTICES (1.275 CM PITCH) OF LOW ENRICHED U(3.3 WT.% U235)O2 FUEL ASSEMBLIES IN LIGHT WATER 75AS(N, 2N), 23NA(N,2N), 90ZR(N,2N), 89Y(N,2N) REACTION RATES, NEA/NSC/DOC(2006)1