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Neutron spectra measurement and calculations using data libraries CIELO, JEFF-3.2 and ENDF/B-VII.1 in iron benchmark assemblies

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Abstract. The leakage neutron spectra measurements have been done on benchmark spherical assemblies - iron spheres with diameter of 20, 30, 50 and 100 cm. The Cf-252 neutron source was placed into the centre of iron sphere. The proton recoil method was used for neutron spectra measurement using spherical hydrogen proportional counters with diameter of 4 cm and with pressure of 400 and 1000 kPa. The neutron energy range of spectrometer is from 0.1 to 1.3 MeV. This energy interval represents about 85 % of all leakage neutrons from Fe sphere of diameter 50 cm and about of 74% for Fe sphere of diameter 100 cm. The adequate MCNP neutron spectra calculations based on data libraries CIELO, JEFF-3.2 and ENDF/B-VII.1 were done. Two calculations were done with CIELO library. The first one used data for all Fe-isotopes from CIELO and the second one (CIELO-56) used only Fe-56 data from CIELO and data for other Fe isotopes were from ENDF/B-VII.1. The energy structure used for calculations and measurements was 40 gpd (groups per decade) and 200 gpd. Structure 200 gpd represents lethargy step about of 1%. This relatively fine energy structure enables to analyze the Fe resonance neutron energy structure. The evaluated cross section data of Fe were validated on comparisons between the calculated and experimental spectra.

1. Introduction

Neutron and gamma spectra behind iron and water layers are long term measured on mock-up of WWER-1000 reactor at LR-0 research reactor in Research Centre, Rez (Czech Republic). Neutron and gamma fields parameters were studied behind iron (reactor pressure vessel model) and water layers. Also corresponding measurements have been done on benchmark iron spherical assemblies with diameter of 20, 30, 50 and 100 cm. The Cf-252 neutron source was placed into the centre of spheres. The measurement results were always compared with parallel MCNP calculations using different data libraries. Two calculations were done with CIELO library [1]. The first one used data for all Fe isotopes from CIELO and the second one CIELO-56 (laboratory name) used only Fe56 data from CIELO. Data for other Fe isotopes were from ENDF/B-VII.1 [2]. The files used for material description in MCNP were in the CIELO: 26054.77C, 26056.77C, 26057.77C, 26058.77C taken from CIELO and in the CIELO56: 26056.77C from CIELO, 26054.72C, 26057.72C, 26058.72C from ENDF/B.

2. Experimental assemblies

Experimental assemblies are formed by the pure iron sphere with diameter of 20, 30, 50, and 100 cm, see Table 1, with neutron source double encapsulated in stainless steel capsule (th. 2× 0.8 mm) placed in centre (transferred by Flexo Rabbit system), see the Fig. 1. Several neutron sources with different emission Q = 1E71E9 n/s were used. The sphere centre and detector centre are always placed at the height of 200 cm above the concrete floor. Shadow (shielding) cone was used for background measurement and subtracting.

Two hydrogen proportional spherical detectors (HPD) K4 and K8 with diameter of 40 mm were used in neutron spectrometer [3]. The detector K4 with pressure 400 kPa was used for measurement in the energy range En = 0.1–0.4 MeV, the detector K8 with pressure 1000 kPa was used for measurement in the energy range En = 0.4–1.3 MeV [3].

3. Methodology of measurement and calculation

To get effect the background measured with shielding cone is subtracted of whole measurement. The calculations were performed using Monte-Carlo program MCNP. For input neutron spectrum is used description from Sajo [4].

As for geometry description, a simplified model was used, which substitutes assembly elements with concentric spherical shells around the source. Also, the MCNP detector is represented by a 1 cm thick spherical shell with radius equal to the real detector-source distance R. For each calculation 10^8–10^9 particle histories were computed.

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Table 1. Iron (Fe) Benchmark assemblies used for measurements and calculations.

Acronym	Fe sphere diam. (cm)	Detector to sphere distance centre to centre (cm)	Max. impurities **) (%w)
FE20	20	100	0.26
FE30	30	100	0.26
FE50	50	100	0.26
FE100	100	150	0.79
FE100	100	53*)	0.79

*) Measurement on the sphere surface **) mainly Mn.

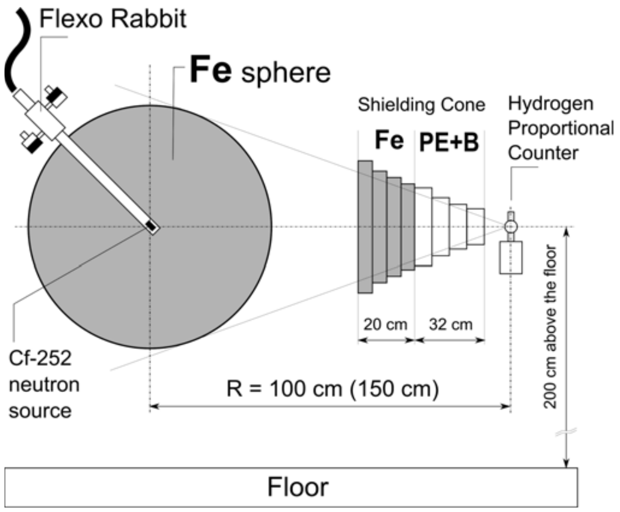

Figure 1. Basic scheme of n-leakage spectrum measurement.

4. Normalisation and smoothing of calculated results, energy structure

The result of neutron spectra calculation and measurement φ(E) is normalised in the following way

$$4\pi R^2\varphi(E)/Q[1/\mathrm{MeV}] \qquad (1)$$

where R is distance between detector and neutron source (centre to centre) and Q [1/s] is neutron source emission rate. Quantity depicted in the figures has the following form and dimension

$$E4\pi R^2\varphi(E)/Q[1] \qquad (2)$$

The integral values presented in following tables are also with dimension of 1.

The measured and calculated spectra were evaluated in two group structures: 40 gpd (groups per decade), it corresponds to the lethargy step about 6% and in structure 200 gpd, i.e., with lethargy step about 1%. Structure 200 gpd is proper only for measurements with very good statistics, but it represents long exposure time. The calculated spectra were usually smoothed by Gaussian with constant percentage resolution Δ of FWHM: $\Delta =$ 13% for 40 gpd and $\Delta = 4\%$ for 200 gpd. The aim of this smoothing is to obtain the form of calculated spectrum similar to measured spectrum with detector of given resolution.

Table 2. Assembly FE100R150, integral values [1], 40 gpd.

Energy range [MeV]			Nuclear data libraries			
from	to	EXP	CIELO	CIELO-56	ENDF	JEFF
0.1	1.3	0.5950	0.6795	0.7081	0.6670	0.6628
0.1	0.2	0.1848	0.2158	0.1872	0.1715	0.2001
0.2	0.4	0.2498	0.3132	0.3444	0.3130	0.2864
0.4	0.8	0.1363	0.1293	0.1548	0.1594	0.1524
0.8	1	0.0154	0.0162	0.0155	0.0146	0.0159
1	1.3	0.0087	0.0050	0.0062	0.0086	0.0080

Table 3. Assembly FE100R150, C/E comparison, 40 gpd.

Energy range [MeV]			Nuclear data libraries			
from	to	EXP	CIELO	CIELO-56	ENDF	JEFF
0.1	1.3	1.000	1.142	1.190	1.121	1.114
0.1	0.2	1.000	1.168	1.013	0.928	1.083
0.2	0.4	1.000	1.254	1.379	1.253	1.147
0.4	0.8	1.000	0.949	1.136	1.169	1.118
0.8	1	1.000	1.053	1.006	0.948	1.032
1	1.3	1.000	0.571	0.713	0.989	0.920

Table 4. Fe assemblies – MCNP calculation with CIELO library, integral values [1], 40 gpd.

Energy range [MeV]		Fe assemblies			
from	to	FE20	FE30	FE50	FE100
0.1	1.3	0.6568	0.7603	0.8442	0.6795
0.1	0.2	0.0602	0.0874	0.1411	0.2158
0.2	0.4	0.1525	0.2102	0.3037	0.3132
0.4	0.8	0.2481	0.2849	0.2852	0.1293
0.8	1	0.0928	0.0916	0.0681	0.0162
1	1.3	0.1032	0.0862	0.0462	0.0050

5. Uncertainties

Uncertainty of single measurement is composed of uncertainty of the “A-type” that include statistical uncertainty of single measurement and consequent calculation of each energy group and uncertainty of “B-type” that include influence of instability in benchmark geometry and detector position, n-source orientation, setting of electronics, detector discharges, energy calibration during time remote repeated measurements. Integral values are presented in Tables 2 and 5 with combined uncertainty in interval 3–7%, where the statistical uncertainty of “A-type” is about 1–3% (for 40 gpd and large energy interval) and the uncertainty of “Btype” is about 3–6%. The statistical uncertainty for 200 gpd (Table 7) is 1–6%. Each measurement was repeated 2–9 times. Uncertainties of MCNP calculations for each group are better than 1% in energy interval 0.1–1.3 MeV.

6. Results

Results are presented at Tables 2–8 and Figs. 2–5. The proper norms (dividing coefficients): 1, 3, 10 and 30 are used in Fig. 2 and Fig. 4 for spectra FE20, FE30, FE50 and FE100 for the better clarity of graphs. More results were presented in 40 gpd structure in [5].

Table 5. Fe assemblies - Experimental values (HPD spectrometer), integral values [1], 40 gpd.

Energy range [MeV]		Fe assemblies			
from	to	FE20	FE30	FE50	FE100
0.1	1.3	0.5850	0.6843	0.7679	0.5950
0.1	0.2	0.0559	0.0790	0.1265	0.1848
0.2	0.4	0.1269	0.1723	0.2489	0.2498
0.4	0.8	0.2148	0.2587	0.2746	0.1363
0.8	1	0.0820	0.0806	0.0609	0.0154
1	1.3	0.1054	0.0937	0.0570	0.0087

Table 6. Fe assemblies – C/E comparison of integral values (Tables 4 and 5), MCNP calculation with CIELO.

Energy range [MeV]			Fe assemblies			
from	to	EXP	FE20	FE30	FE50	FE100
0.1	1.3	1.000	1.123	1.111	1.099	1.142
0.1	0.2	1.000	1.077	1.107	1.115	1.168
0.2	0.4	1.000	1.202	1.220	1.220	1.254
0.4	0.8	1.000	1.155	1.101	1.039	0.948
0.8	1	1.000	1.132	1.135	1.120	1.054
1	1.3	1.000	0.979	0.920	0.810	0.572

Table 7. FE100R53 assembly, fine structure 200 gpd.

Energy range [MeV]			Integral values [1]		
from	to	EXP	ENDF	CIELO	JEFF
0.013	1.290	1.0442	1.0914	1.1124	1.1131
0.013	0.033	0.1547	0.1403	0.1445	0.1526
0.033	0.060	0.0299	0.0265	0.0249	0.0292
0.060	0.090	0.0813	0.0770	0.0776	0.0795
0.090	0.150	0.1576	0.1318	0.1662	0.1589
0.150	0.200	0.1047	0.0959	0.1189	0.1069
0.200	0.250	0.0649	0.0663	0.0656	0.0663
0.250	0.290	0.0794	0.0870	0.0835	0.0812
0.290	0.330	0.0905	0.1351	0.1276	0.1165
0.330	0.400	0.0816	0.1081	0.1160	0.1040
0.400	0.520	0.0537	0.0570	0.0511	0.0595
0.520	0.780	0.1146	0.1364	0.1100	0.1263
0.780	1.060	0.0238	0.0231	0.0224	0.0256
1.060	1.290	0.0074	0.0070	0.0042	0.0066

Table 8. 1-C/E, FE100R53 assembly, fine structure 200 gpd.

Energy range [MeV]			1-C/E [%]		
from	to	EXP	ENDF	CIELO	JEFF
0.013	1.290	0.00	4.52	6.54	6.60
0.013	0.033	0.00	−9.30	−6.61	−1.33
0.033	0.060	0.00	−11.49	−16.87	−2.43
0.060	0.090	0.00	−5.36	−4.58	−2.19
0.090	0.150	0.00	−16.36	5.44	0.80
0.150	0.200	0.00	−8.37	13.54	2.12
0.200	0.250	0.00	2.18	1.19	2.16
0.250	0.290	0.00	9.61	5.23	2.32
0.290	0.330	0.00	49.15	40.88	28.66
0.330	0.400	0.00	32.41	42.08	27.37
0.400	0.520	0.00	6.12	−4.93	10.84
0.520	0.780	0.00	19.02	−4.00	10.18
0.780	1.060	0.00	−2.78	−5.70	7.63
1.060	1.290	0.00	−6.34	−42.95	−10.88

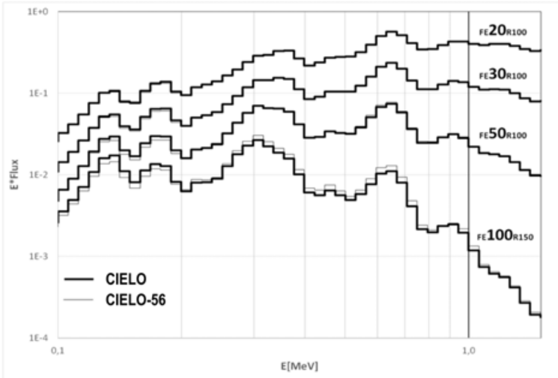

Figure 2. CIELO and CIELO-56: Comparison of calculated spectra Fe assemblies - diam. 20,30,50,100 cm, 40 gpd.

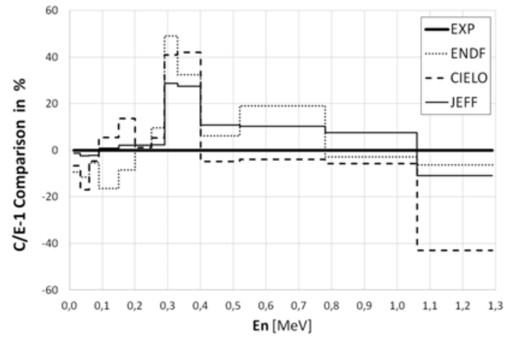

Figure 3. CALC/EXP-1, assembly FE100, R=53, fine structure 200 gpd, see Table 8.

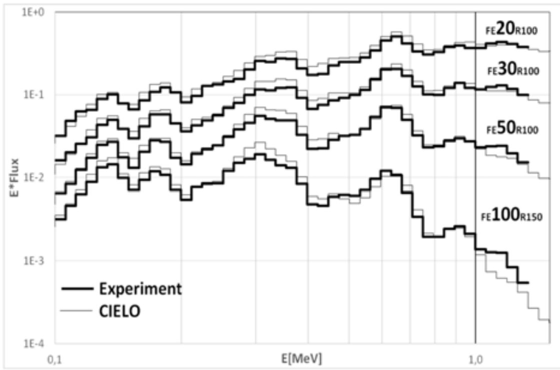

Figure 4. Comparison of calculated and measured spectra (CIELO and Experiment), Fe 20, 30, 50 and 100 cm, 40 gpd (proper norms were used).

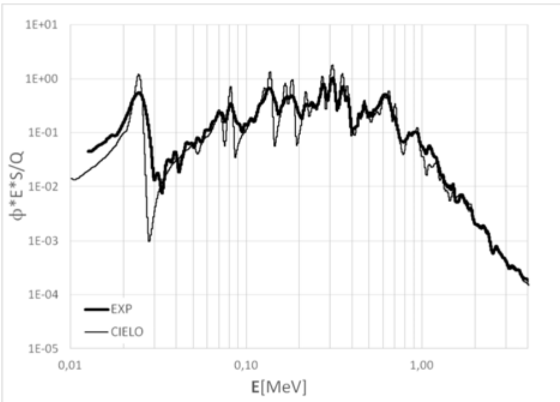

Figure 5. Assembly FE100, R = 53, Comparison of Measured (thick) and calculated with CIELO (thin) spectra in structure 200 gpd.

7. Conclusions

Based on data presented in tables and pictures it is possible to conclude:

1) Table 3: For assembly FE100, R150 and all libraries in interval 0.1–1.3 MeV is the C/E = 1.11–1.19.
2) Table 6: For FE20, 30, 50, 100 and library CIELO in interval 0.1–1.3 MeV is the C/E = 1.10–1.14.
3) Items 1) and 2) indicate **systematic calculation overestimation of 10–14%** in this region (of course, it could be measurement underestimation). The identical assembly FE50R100 was measured in past years at Rez by colleagues from Skoda Plzen (M.Holman) and from FEI Obninsk (L.Trykov) using independent (but also proton recoil) spectrometers. Their results are not more different than about 1–5% in region 0.1–1.3 MeV in comparison with our results.
4) Tables 2 and 3 represent comparison of CIELO and CIELO-56 libraries. Regarding our experimental experiences with Iron filtered beams from past years, when using older versions of Data Libraries (ENDF, BROND, JENDL) two general rules were observed: **C/E < 1 for 0.1–0.2** MeV and **C/E>1 for 0.2–0.4** and **0.4–0.8** MeV (two characteristic wide Iron peaks around 0.3 MeV and 0.6 MeV). When we compare CIELO/CIELO-56, we can observe the **"proper improving trend"** in above mentioned regions when new Fe-54 (and Fe-57 and Fe-58, of course) new cross section (CS) in CIELO is used. It indicates the **important role of Fe-54 CS** for Iron neutron transport calculations although the content of Fe-54 in natural Fe is only 5.8%. Also, influence of other two isotopes in natuaral iron should be taken into account (the content of Fe-57 is 2.2% and content of Fe-58 is 0.28%).
5) When analysing the influence of Fe-54 in whole energy interval it seems that the **significant differences between calculations using CIELO and CIELO-56 are observed for En < 1 MeV.** Analyse of results indicates that the **role of Fe-54 increases with Fe slab thickness**, see Fig. 2. For En>1 MeV is the influence of Fe-54 minimal.
6) Figure 4 indicates that peak on 0.6 MeV is shifted (relating to experiment) for CIELO. The probably reason is the relation between heights of the 0.610, 0.641 and 0.702 MeV peaks that at are visible only in fine neutron energy structure 200 gpd, see Fig 5. The peak 0.702 MeV is probably unrealistic dominant for CIELO.
7) Figure 4 and Tables 3 and 6 indicate that in energy interval 1–1.3 MeV the ratio C/E for CIELO (not for ENDF and JEFF) **decreases rapidly with Fe thickness from the value 0.98 (Fe20) to the 0.57 (Fe100).** Neutron absorption cross section is unrealistic high in the region 1–1.3 MeV.

We can conclude that CIELO brings not a great improvement of C/E ratio in the region 0.1–1.3 MeV in comparison with ENDF and JEFF. It is necessary to emphasize the great role of Fe-54 cross section in natural Fe.

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