Neutron Spectra Measurement and Calculations Using Data Libraries CIELO, JEFF-3.2 and ENDF/B-VII.1 in Spherical Iron Benchmark Assemblies

Jansky Bohumil[1], Rejchrt Jiri[1], Novak Evzen[1], Losa Evzen[1],
Blokhin Anatoly[2], Mitenkova Elena[3]

[1]*Department of Neutron Physics, Research Centre, Rez, Czech Republic*
[2]*Lt'd Company "The Material Laboratory of Institute for Nuclear Power Engineering", Obninsk, Russia*
[3]*Nuclear Safety Institute of Russian Academy of Sciences, Moscow, Russia*

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Proposed topic: Integral experiments, benchmarks and data validation

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 pressure of 400 and 1000 kPa. Diameter of used detectors was 4 cm. The neutron energy range of spectrometer was from 0.1 to 1.3 MeV. This energy interval represents about 84% of all leakage neutrons from Fe sphere of diameter 50 cm and about of 75% for Fe sphere of diameter 100 cm. The adequate MCNP neutron spectra calculations based on data libraries CIELO and JEFF-3.2 and ENDF/B-VII.1 were done. The neutron energy structure used for calculations and measurements was 40 groups per decade (gpd) represents lethargy step about of 6%. This relatively fine energy structure enables to analyze the Fe resonance neutron energy structure. The evaluated cross section integral data of Fe were validated on comparisons between the calculated and experimental spectra.

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 Center, Rez (Czech Republic). Neutron and gamma field's 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. The following data libraries were used: CIELO [1] (with Fe-56 and Fe-54 cross sections) and CIELO-6 (internal acronym for library with Fe-56 cross section only), JEFF-3.2 and ENDF/B-VII.1.

Authors assume that the already performed measurement results can serve as integral validation of various data libraries.

Experimental assemblies

Experimental assemblies are formed by the pure iron sphere with diameter of 20, 30, 50, and 100 cm with neutron source placed in centre, see Table 1.

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

Acronym	DIA – iron sphere diameter [cm]	R -detector to sphere distance centre to centre [cm]
FE20R100	20	100
FE30R100	30	100
FE50R100	50	100
FE100R150	100	150

The pneumatic flexo-rabbit system is used for neutron source transport from shielding container to measuring place and back, see the Fig.1. The sphere centre and detector centre are always placed at the height of 200 cm above the concrete floor. Shadow cone was used for background measurement. Two hydrogen proportional spherical detectors (HPD) K4 and K8 with diameter of 40 mm were used in neutron spectrometer. 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[2].

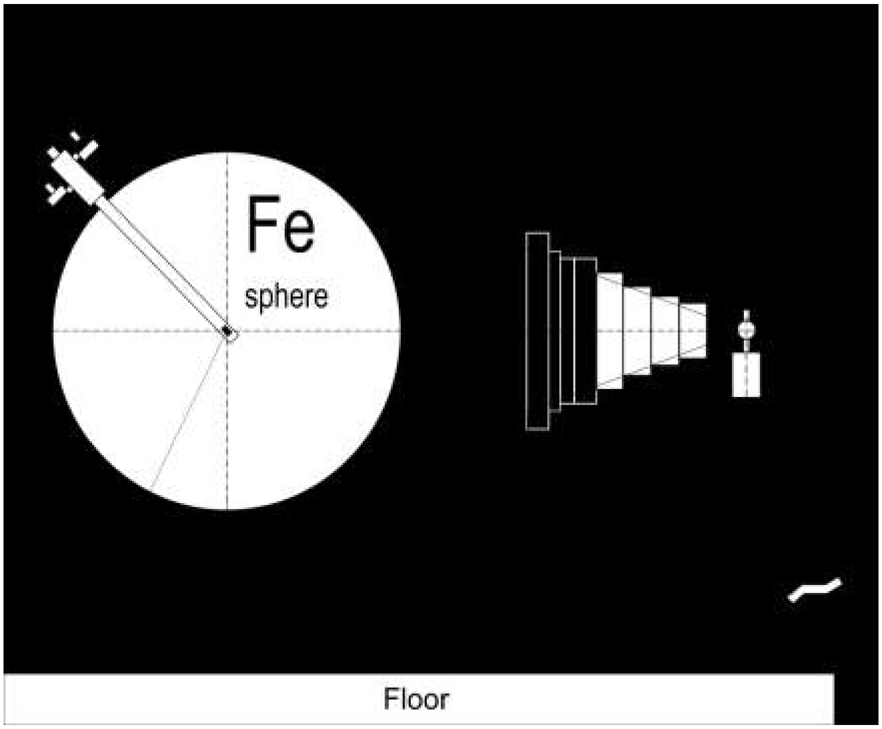

Figure 1.The basic scheme of n-leakage spectrum measurement.

Methodology of measurement and calculation

The background of the measured neutron field is determined by additional measurement performed with shielding cone, see Fig.1. The shielding cone has to shield corresponding space angle to measure all unwelcome scattered neutrons (from walls, floor, air), and laboratory background neutrons (e.g., sources in container). Background is then subtracted of whole measurement to get just “pure” Fe leakage spectrum.

The calculations were performed using Monte-Carlo program MCNP. 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 1cm thick spherical shell with radius equal to the real detector-source distance R. For each calculation $10^8 - 10^9$ particle histories were computed.

Normalisation and smoothing of calculated results, energy structure

The result of neutron spectra calculation and measurement $\varphi(E)$ is normalized in the following way

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

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

$$E 4\pi R^2 \varphi(E) / Q \quad [\ 1\ ]. \tag{2}$$

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

The measured and calculated spectra were evaluated in two group structures:

a) 40 gpd (group per decade) – it corresponds to the lethargy step about 6%,
b) 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:

$$\Delta = 13\% \text{ for } 40 \text{ gpd and } \Delta = 4\% \text{ for } 200 \text{ gpd.}$$

The aim of this smoothing is to obtain the form of calculated spectrum similar to measured spectrum with detector of given resolution.

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. Both types of uncertainties (A and B) have been combined using the errors propagation rule for resulting uncertainty of values of each energy group. Each measurement was repeated 2 – 9 times. Uncertainties of the integral values presented in tables are in interval from 1 to 3%.

Uncertainties of MCNP calculations are better than 1% in energy interval 0.1–1.3 MeV.

Results

Although MCNP calculations had been performed in wider energy interval (from 1E-8 to 22 MeV), regarding to the neutron spectrometer energy range, i.e., to the experimental data, all the tables and graphs contain data limited for energy interval from 0.1 to 1.3 MeV. This energy interval represents about 66% of all leakage neutrons from Fe sphere with diameter of 20 cm (66% from FE20), 76 % from FE30, 84% from FE50 and 75% from FE100. These values were derived from spectra calculated with ENDF library. The proper norms (dividing coefficients), 1, 3, 10 and 30 are used for spectra FE20, FE30, FE50 and FE100 for the better clarity of graphs.

Table 2. Assembly FE100R150, integral values (2)

Energy range [MeV]		**Nuclear data libraries**				
from	to	**EXP**	**CIELO**	**CIELO-6**	**ENDF**	**JEFF**
0.1	1.3	0.5950	0.6783	0.7081	0.6670	0.6628
0.1	0.2	0.1848	0.2156	0.1872	0.1715	0.2001
0.2	0.4	0.2498	0.3080	0.3444	0.3130	0.2864
0.4	0.8	0.1363	0.1342	0.1548	0.1594	0.1524
0.8	1	0.0154	0.0147	0.0155	0.0146	0.0159
1	1.3	0.0087	0.0057	0.0062	0.0086	0.0080

Table 3. Assembly FE100R150, the C/E comparison

Energy range [MeV]		**Nuclear data libraries**				
from	to	**EXP**	**CIELO**	**CIELO6**	**ENDF**	**JEFF**
0.1	1.3	1.00	1.14	1.19	1.12	1.11
0.1	0.2	1.00	1.17	1.01	0.93	1.08
0.2	0.4	1.00	1.23	1.38	1.25	1.15
0.4	0.8	1.00	0.98	1.14	1.17	1.12
0.8	1	1.00	0.96	1.01	0.95	1.04
1	1.3	1.00	0.66	0.71	0.99	0.92

Table 4. Fe assemblies – MCNP calculation with CIELO library, integral values (2)

Energy range [MeV]		**Fe assemblies**			
from	to	**FE20R100**	**FE30R100**	**FE50R100**	**FE100R150**
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

Table 5. Fe assemblies – Experimental values (HPD spectrometer), integral values (2)

Energy range [MeV]		**Fe assemblies**			
from	to	**FE20R100**	**FE30R100**	**FE50R100**	**FE100R150**
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, integral values

Energy range [MeV]		**Fe assemblies**			
from	to	**FE20R100**	**FE30R100**	**FE50R100**	**FE100R150**
0.1	1.3	1.123	1.111	1.099	1.142
0.1	0.2	1.077	1.107	1.115	1.168
0.2	0.4	1.202	1.220	1.220	1.254
0.4	0.8	1.155	1.101	1.039	0.948
0.8	1	1.132	1.135	1.120	1.054
1	1.3	0.979	0.920	0.810	0.572

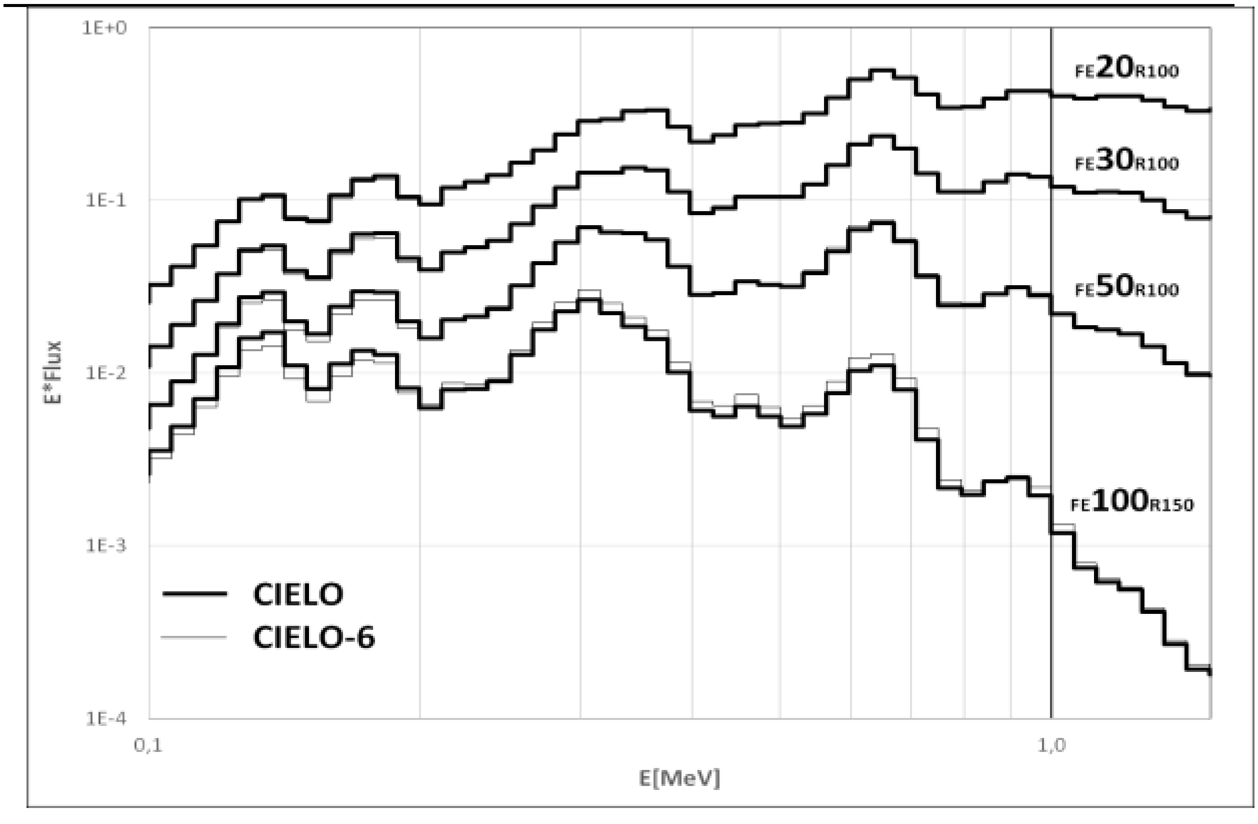

Figure 2. CIELO and CIELO-6: Comparison of calculated spectra
Fe assemblies – diam. 20, 30, 50, 100 cm, 40 gpd.

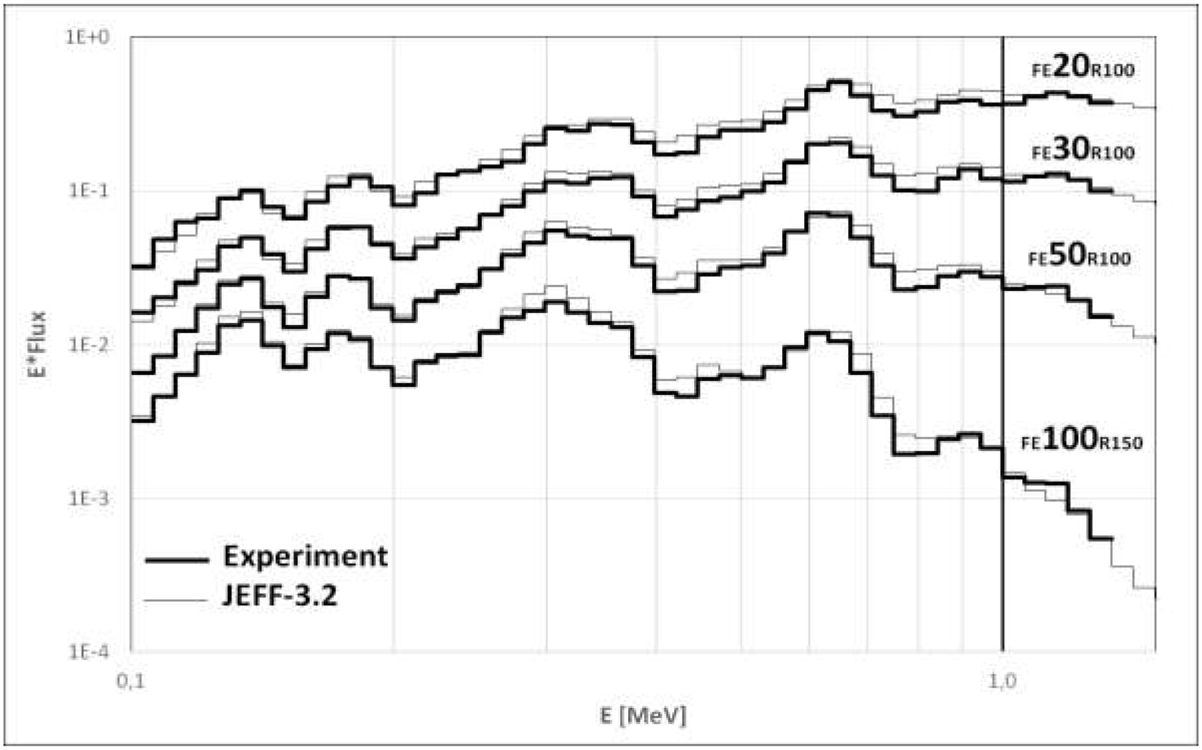

Figure 3. JEFF-3.2 and Experiment: Comparison of calculated and measured spectra Fe assemblies – diam. 20, 30, 50 and 100 cm, 40 gpd.

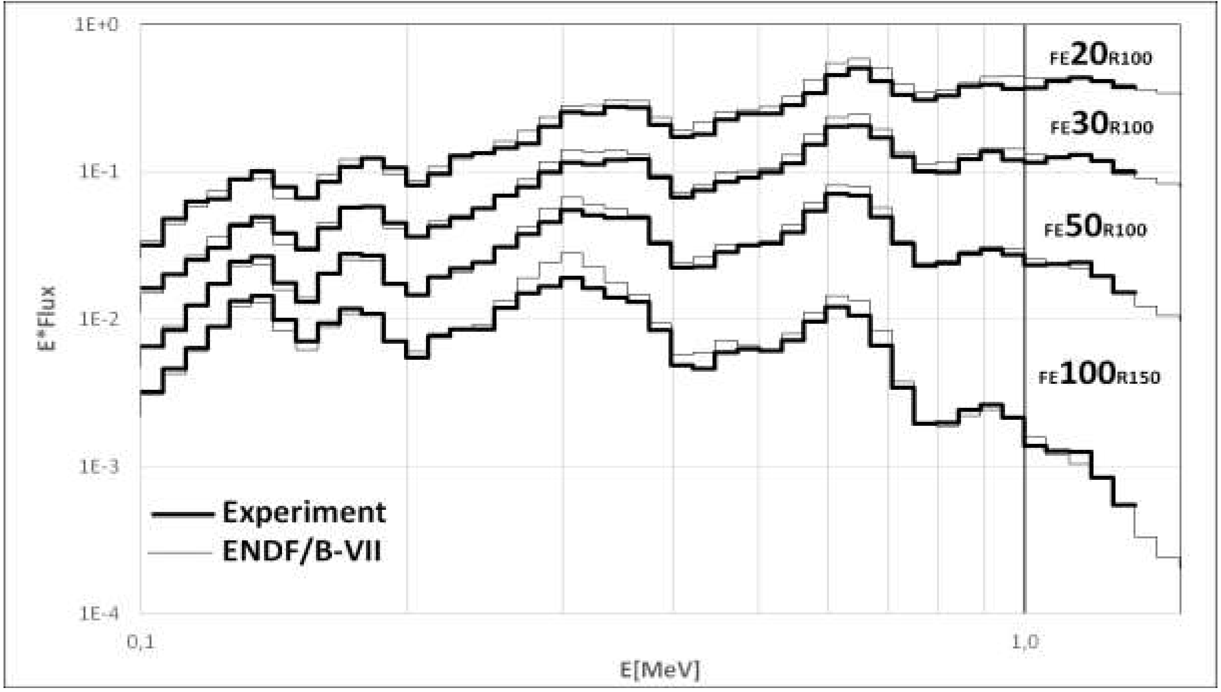

Figure 4. ENDF/B-VII and Experiment: Comparison of calculated and measured spectra Fe assemblies – diam. 20, 30, 50 and 100 cm, 40 gpd.

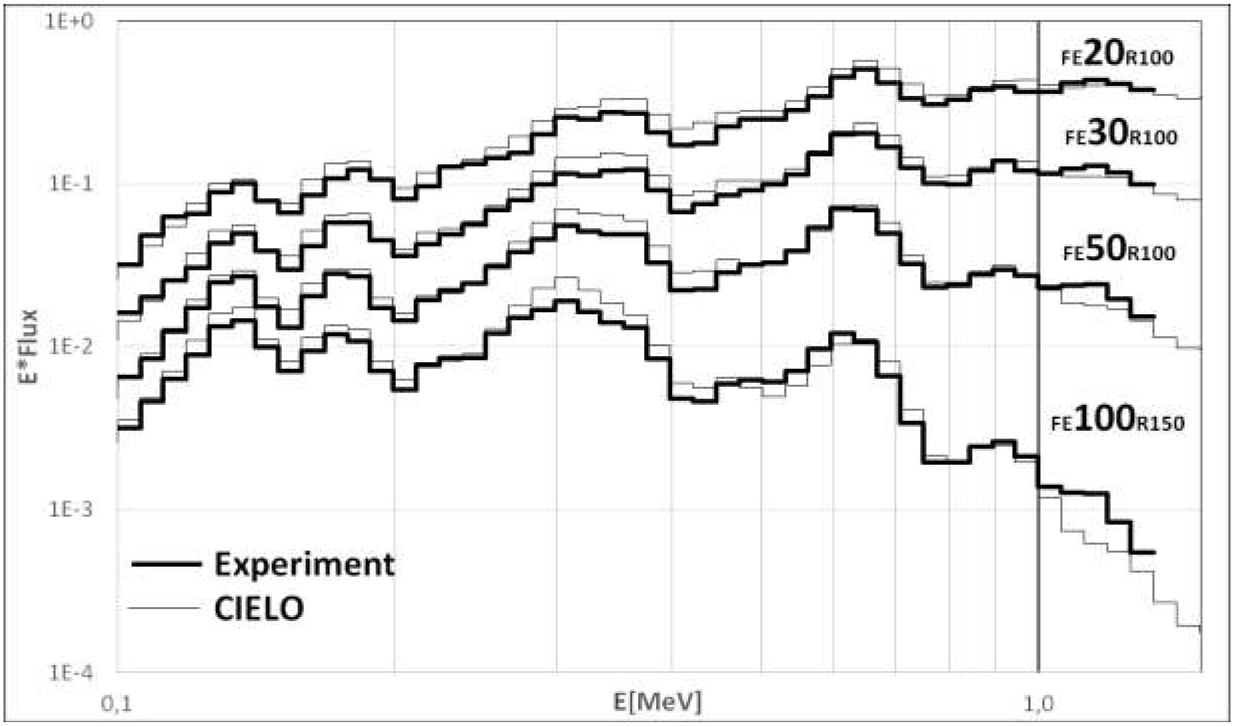

Figure 5. CIELO and Experiment: Comparison of calculated and measured spectra Fe assemblies – diam. 20, 30, 50 and 100 cm, 40 gpd.

Conclusions

1) Tab.3: For assembly FE DIA100, R150 and all libraries in interval 0.1–1.3MeV is the C/E = 1.11–1.14.
2) Tab.6: For FE 20, 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 n-calculation overestimation 10–14 % in this region (or measurement underestimating?). The identical assembly FE DIA50, R100 was measured in past in Rez by colleagues from Skoda Plzen (M. Holman) and from FEI Obninsk (L. Trykov) using independent (proton recoil) spectrometers. Their results are not higher than about 1–5 % in region 0.1–1.3MeV in comparison with ours.
4) Fig.2 .and tab.2 and tab.3 represent comparison CIELO and CIELO-6 libraries. Regarding our experimental experiences with Iron filtered beams , from last years when using old versions of Data Libraries (ENDF, BROND, JENDL), it was observed those general rules: C/E<1 for 0.1-0.2 MeV and C/E >1 for 0.2–0.4 and 0.4–0.8 MeV. When we compare CIELO/CIELO-6, we observed the “proper trend” in above mentioned regions when new Fe-54 cross section (CS) in CIELO is used. It indicates the important role of Fe-54 CS for iron neutronic transport calculations although the content of Fe-54 in natural Fe is only 5.8 %. Fig. 2 indicates, that the role of Fe-54 increase with Fe slab thickness.
5) When analysing the influence of Fe-54 in whole energy interval it seems that the relevant difference between CIELO and CIELO6 is for En<1MeV. For En>1MeV the influence of Fe-54 is minimal.

6) Figs.3, 4, 5 indicates that peak on 0.6 MeV is shifted (relating to measured spectrum) for CIELO and JEFF, not for ENDF. The reason is probably the proportions between peaks 0.610, 0.641 and 0.702 MeV which are resolved only in fine neutron energy structure 200gpd. For CIELO and JEFF is probably peak 0.702 MeV unrealistic dominant.
7) Fig.5 and Table 6 indicates 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 0.98 (Fe20) to 0.57 (Fe100). Neutrons are probably in this region 1–1.3MeV unrealistic absorbed.
8) We can conclude that CIELO not brings a great improvement C/E in the region 0.1–1.3 MeV compared with ENDF and JEFF. It is necessary to emphasize the great role of Fe-54 cross section in natural Fe.

References

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