International Atomic Energy Agency

INDC(CCP)-314
Distr.: L+F

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INTERNATIONAL NUCLEAR DATA COMMITTEE

THE NEUTRON LEAKAGE SPECTRUM FOR AN IRON SPHERE WITH A CENTRAL 14 MeV NEUTRON SOURCE

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(English translation by IAEA of the Russian report
IAE-4990/8, Moscow 1989)

May 1990

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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Reproduced by the IAEA in Austria
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90-02378

1. INTRODUCTION

Among the numerous problems of materials technology arising in fusion reactor design, those of developing structural materials for the first wall, blanket and radiation shield are crucial. It is on the successful solution of these problems that the realization of the idea of using controlled nuclear fusion to produce power or fissile nuclides will to a great extent depend.

As is shown by the papers presented at the 15th Symposium on Fusion Technology (September 1988, Netherlands), preference is currently given to stainless steel 316L [1]. This grade of steel is proposed for use in the main components of the vacuum chamber, blanket and biological shield of the international ITER reactor. The proportion of steel components in the blanket is expected to be quite high. Such components are the fuel assembly cladding, coolant channel casings, spacer grids, etc. It is believed that even optimizing the material composition of the blanket will scarcely reduce the proportion of structural materials to below 20% by volume [2].

The influence of steel structures on the neutron-physics parameters of the blanket was investigated in a number of studies, for example Refs [2-4]. It follows from the data of Ref. [2] that the plutonium breeding ratio in the uranium blanket of a hybrid fusion reactor changes at the rate of ~ 1% for each 1% content of iron in the U-Fe mixture. The influence of iron on the tritium conversion factor K_t is equally significant [3]. Addition of only 6% iron to the beryllium neutron multiplier reduces K_t from 1.55 to 1.31 (this is in the specific case of a lithium-containing blanket). It is clear that for this scale of effect the influence of iron on the neutron-physics parameters of the blanket cannot be neglected.

In this connection it is necessary to evaluate the accuracy of the neutron data for iron in the $\leq$ 14 MeV region. One of the possibilities is benchmark testing of the calculation on the basis of the results of integral experiments, of which quite a few have been performed on iron [5-9]. Unfortunately, as we show below, the results of these measurements are contradictory and cannot be used to conclude unambiguously about the reliability of the nuclear data on Fe.

In our opinion, the reliability of an integral experiment can be improved by arranging it so that the whole set of parameters characterizing the neutron-physics properties of the material is measured. We are referring to measurement, using the same assembly, of the neutron and gamma-ray leakage spectra, the spatial distributions of the rates of the (n,p), (n,α) and (2,2n) reactions for iron nuclei and the threshold activation reactions with subsequent unfolding of the neutron spectra in the volume of the assembly.

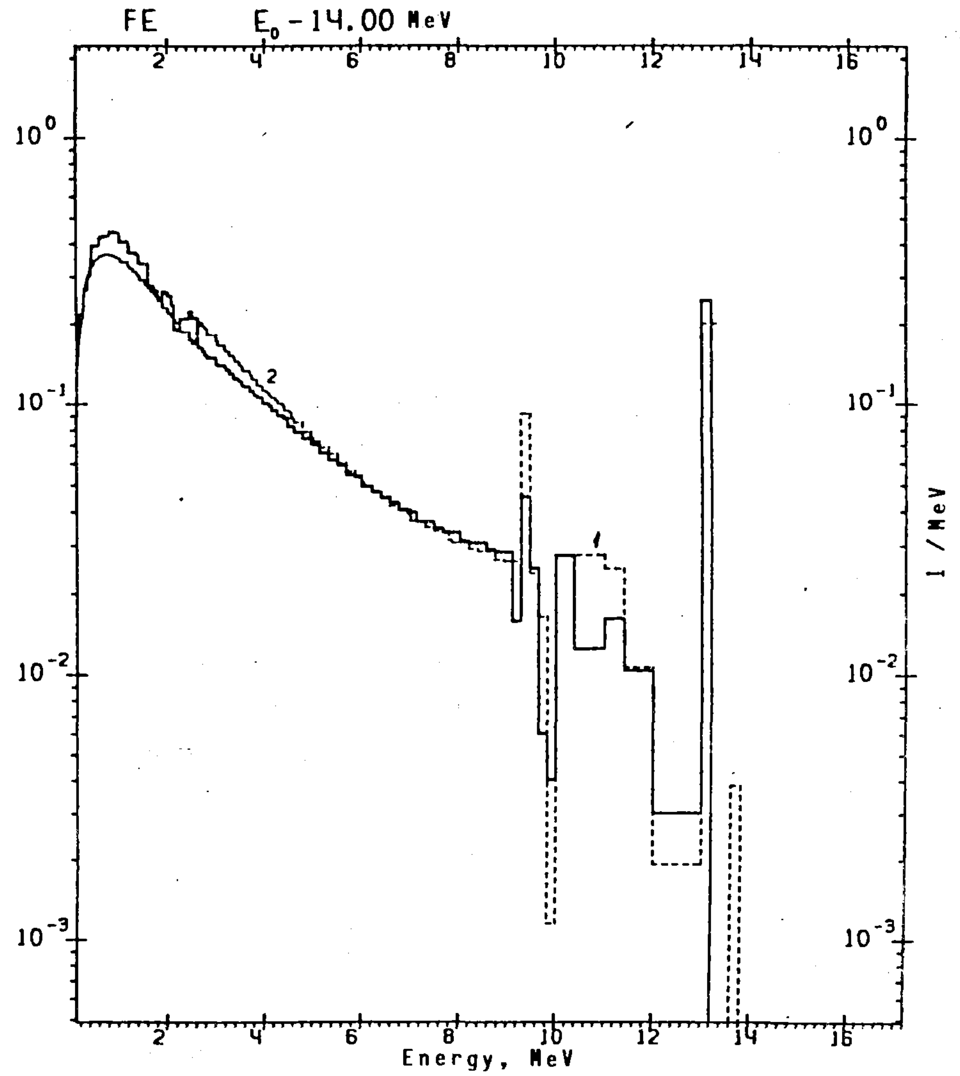
In this work, we give measurement results and compare them with calculations of the neutron leakage spectrum for an iron sphere with a wall thickness of 7.5 cm (or 1.6 mean free paths for 14 MeV neutrons) in the 1-15 MeV region. The measurements were performed with a scintillation spectrometer. Later, using the same assembly, we plan to measure the neutron leakage spectrum by the time-of-flight technique and also the above parameters.

2. PRESENT STATUS OF NEUTRON DATA FOR NATURAL IRON

Table 1 gives the main interaction cross-sections for 14 MeV neutrons with natural iron from a number of evaluated nuclear data libraries used for validating the designs of fusion reactor blankets.

Table 1.

Library	ENDL-75	ENDL-83	ENDF/B-IV	JENDL	BROND
σ_t	2.618	2.619	2.571	2.520	2.586
σ_{el}	1.172	1.172	1.171	1.245	1.265
σ_{in}	1.286	1.186	1.181	1.043	1.084
$\sigma_{n,2n}$	0.377	0.275	0.432	0.422	0.400
σ_{cont}	0.850	0.850	0.632	0.619	0.513



			$\gamma_{nn'}$	$\gamma^{>0.10}$	$\bar{E}$
(1) —— ENDF-4	MAT=1192		1.340	1.322	3.19
(2) ----- BROND	MAT=2600		1.333	1.323	3.67

Fig. 1.

TOTAL DIFFERENTIAL SPECTRUM
OF INELASTICALLY SCATTERED
NEUTRONS

The highest difference, of up to ~ 25%, is observed in the total inelastic cross-section σ_{in} and also in the ratios of the partial channels of this reaction. While the share of the (n,2n) reaction in σ_{in} is 37-40% in the case of ENDF/B-IV, JENDL-2 and BROND, it is only 23% in ENDL-83.

The total emission spectrum normalized to a single neutron-nucleus collision event can serve as the common characteristic of data for a given incident neutron energy. Such spectra were calculated on the basis of multigroup constants prepared from evaluated data files and intended for neutron transport calculation in the region above 0.1 MeV by the BLANK program [10]. The emission spectrum is the sum of the energy spectra of all scattering processes taken with their respective weights provided that the inelastically scattered neutrons are isotropic. As an example, Fig. 1 shows the emission spectra from ENDF/B-IV and BROND for the initial energy of 14 MeV. Table 2 gives the values of the average emission spectrum energy $\bar{E}$ and the neutron yield ν for the different energy regions.

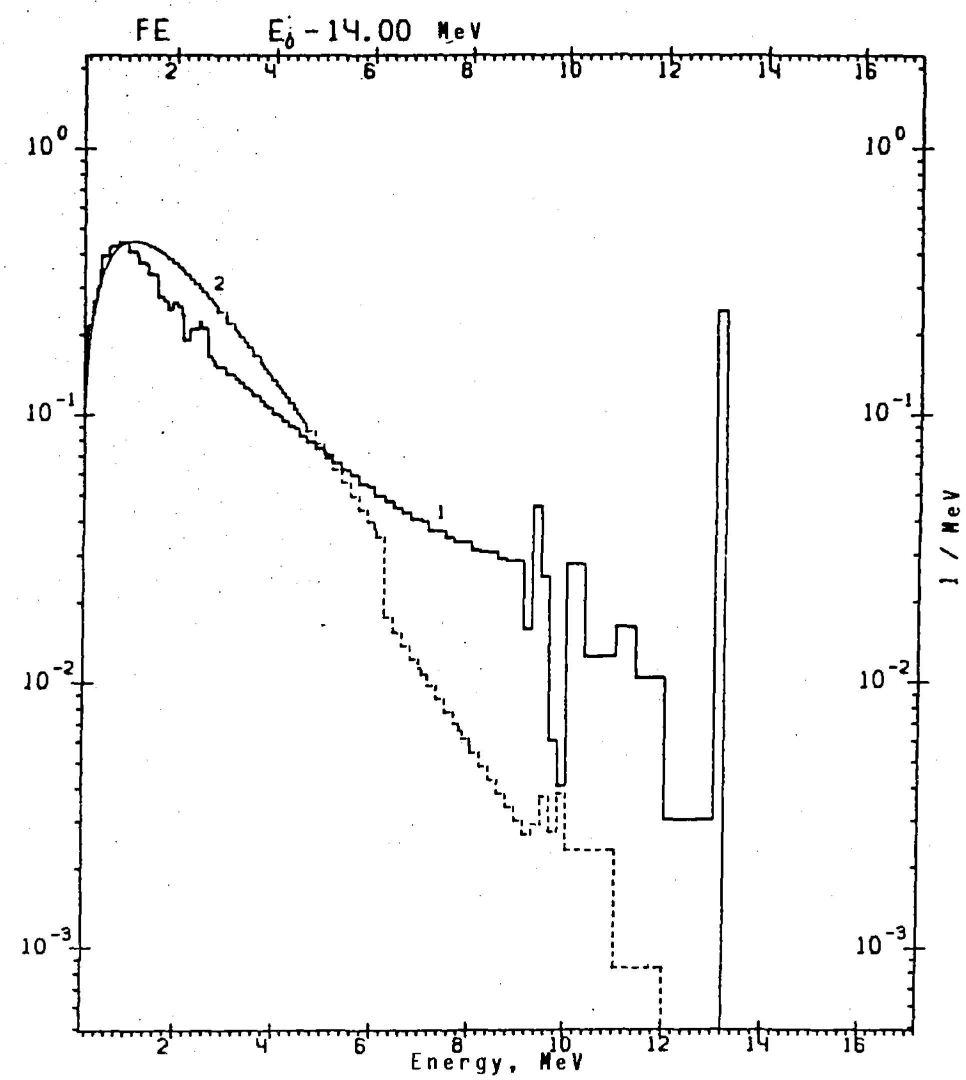
Table 2.

Library	$\bar{E}$, MeV	$\nu(E)$ 0-15 MeV	10-15 MeV	5-10 MeV	1-5 MeV
ENDF/B-IV	7.63	1.100	0.496	0.084	0.349
JENDL-2	7.41	1.079	0.494	0.019	0.400
BROND	8.28	1.092	0.547	0.088	0.322
ENDL-83	8.43	1.006	0.497	0.097	0.283
ENDL-75	7.90	1.086	0.498	0.097	0.313

A considerable scatter of ν values is particularly noticeable in the 1-5 MeV region, where about 30% of all neutrons emitted are concentrated. The neutron yields in this region differ by a factor of up to ~ 1.5. In the 5-10 MeV region, the ν values are fairly close for the different libraries - except JENDL-2, according to whose data the neutron yield for this energy is lower by a factor of 4-5. This is due to the fact that JENDL-2 uses the representation of the energy distribution of inelastically scattered neutrons in the form of an evaporation spectrum (see Fig. 2). The other libraries take into account that at incident neutron energies of ~ 14 MeV the so-called direct processes may occur, bypassing the compound nucleus stage, with the result that the neutron fluxes in the 5-10 MeV region are substantially higher than for the evaporation spectrum. For $E \geq 10$ MeV, where the spectrum is determined mainly by elastic scattering, the neutron yield is 0.49-0.50 except in the BROND file, where ν is 10% higher owing to the contribution of inelastic scattering with excitation of discrete levels.

The average spectrum energy normalized to a single scattered neutron ($\bar{E}/\nu$) varies over the range 6.9 MeV/n (ENDF/B-IV)-8.4 MeV/n (ENDL-83). We thus note that there is a substantial spread in the basic parameters for the interaction of 14 MeV neutrons with iron.

The natural criterion for selecting the best nuclear data version is comparison of calculation with experimental results. Above we referred to the large number of experiments on iron. In their approach, the spherical shell experiments performed at the Livermore Laboratory [5, 6] and at the University



			ν_{tot}	$\nu^{>0.10}$	$\bar{E}$
(1)	—— ENDF-4	MAT=1192	1.340	1.322	3.19 МэВ
(2)	----- JENDL2	MAT=2260	1.386	1.380	2.27 МэВ

Fig. 2.

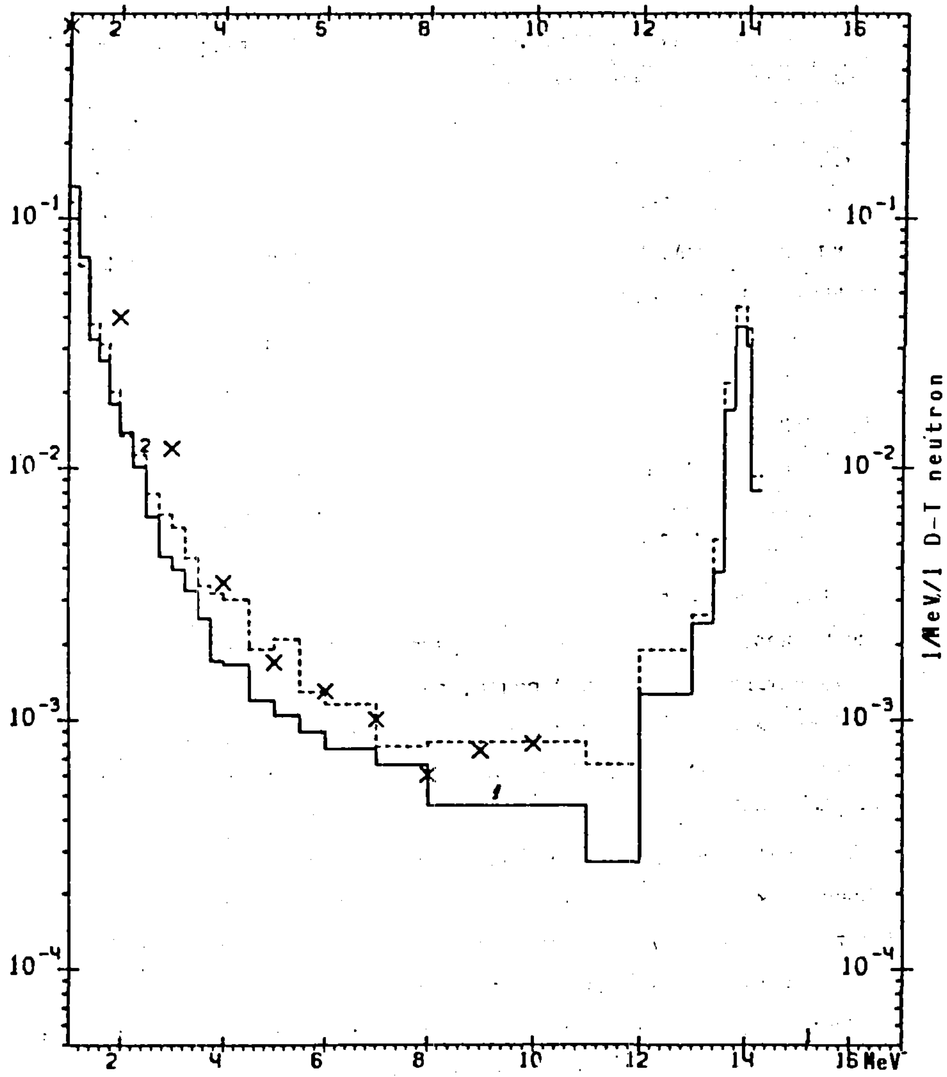
TOTAL DIFFERENTAIL SPECTRUM
OF INELASTICALLY SCATTERED
NEUTRONS

of Illinois [8, 9] are the most appropriate for purposes of benchmark testing of nuclear data. Unfortunately, their conclusions are substantially contradictory. Thus, experiments on a time-of-flight spectrometer with iron spheres having wall thicknesses of 4.46, 13.4 and 22.3 cm [5, 6] showed only a 20% difference from calculation in the leakage spectra in the 2-10 MeV region. The ENDF/B-IV data were were used in the calculation. On the other hand, in the experiments [8, 9], where the neutron leakage spectrum was measured for a sphere with a wall thickness of 30.45 cm on a scintillation detector, the difference from calculation using the same nuclear data was by a factor of 2-3. In such a situation it is difficult to give preference to any of the experiments, not to mention selecting a better version of the data.

The model of the experiment for an iron sphere with a wall thickness of 30.45 cm [9] was calculated by the one-dimensional BLANK program with the FORTON-88 physical module [11]. The evaluated data files ENDL-75, ENDL-83,

Table 3.

Energy Region MeV	Exp. [9]	VIM	BLANK ENDL75	ENDL83	F/B-IV	JENDL	BROND
5 - 10	5.0-4	4.4-4	10.-4	10.-4	10.-4	6.-4	12.-4
2.23-5	5.6-3	4.1-3	4.-3	4.-3	4.-3	4.7-3	4.5-3
1-2.23	8.7-2	5.1-2	3.3-2	3.1-2	3.8-2	3.6-2	3.7-2



$\bar{E}_{source}$ - 14.10 MeV Thick-ness - 30.45 cm, BLANK - 3×10^5 histories

		M_{TOT}
ENDF-4	(1) ——	1.295
BROND	(2) -----	1.292

Fig. 3.

DIFFERENTIAL SPECTRUM OF NEUTRON LEAKAGE FROM THE FE SPHERE

Table 4.

Energy Region MeV	Exp. [9]	Neutron leakage ANISN DLC-41	ENDL75	BLANK ENDL83	F/B-IV	JENDL	BROND
10-15	2.0-2	1.9-2	1.9-2	1.9-2	1.8-2	2.3-2	2.4-2
5-10	5.3-3	3.5-3	4.0-3	4.0-3	3.0-3	1.0-3	5.0-3
2.23-5	2.3-2	1.0-2	1.4-2	1.3-2	1.0-2	1,3-2	1.3-2
1-2.23	1.9-1	0.62-1	0.53-1	0.48-1	0.59-1	0.64-1	0.57-1

ENDF/B-IV, JENDL-2 and BROND were used. As in Ref. [9], the spectra were calculated for two types of source - ^{252}Cf fission neutrons and 14 MeV neutrons. The results of calculations made for 200 000 and 300 000 neutron histories, respectively, are given in Tables 3 and 4. The spectra are normalized to a single source neutron.

Figure 3 shows the neutron leakage spectra for a spherical iron assembly at an initial neutron energy of 14 MeV, which were calculated on the basis of the ENDF/B-IV and BROND files and measured experimentally. As will be seen from Fig. 3 and Table 4, in the region below 10 MeV the calculated values of leakage neutron flux are systematically lower than the experimental data. The difference is by a factor of up to 2-4. A similar situation is observed also for the californium source. Here, too, calculation gives substantially lower leakage neutron fluxes.

It is thus not possible to draw any reliable conclusions about the accuracy of a particular nuclear data library. Further experiments are necessary.

3. EXPERIMENT

The neutron leakage spectrum was measured on a J-15 neutron generator. The deuteron energy was 120 keV for a target current of 50 μA. The target was a molybdenum disc, 45 mm in diameter and 0.4 mm in thickness, coated with a 1.75 mg/cm^2 thick Ti-T layer. The target was cooled by running water. The thickness of the water layer was 2 mm. The maximum neutron yield was 10^9 n/s, which was measured from the associated alpha particles with the help of a DKPS-25 silicon surface-barrier detector installed in the ion conductor at a distance of 300 mm from the target at an angle of 171° to the deuteron beam.

The neutrons were recorded with a liquid organic scintillator, NE-213, having a diameter and height of 5.08 cm. The distance between the neutron generator target and the spectrometer detector was 3 m.

In order to eliminate the background of neutrons scattered from the walls of the experimental room and the process equipment, we used a steel shadow cone. Its dimensions were so chosen that during measurement of the background only the lead sphere had to be shielded and both the secondary neutrons generated in the assembly and the source neutrons could be fully eliminated. The measurements were performed twice - without and with the shadow cone. Thereafter, the instrument spectra normalized to one source intensity were subtracted.

The spectra were normalized to a single source neutron. The neutron yield Y_n was determined from the following expression

$$Y_n = \frac{1}{\varepsilon_\alpha} R_\alpha C_\alpha$$

where C_α is the count of the associated alpha-particle detector, ε_α the efficiency of recording of alpha particles by the silicon surface-barrier detector and R_α the coefficient of anisotropy of alpha-particle emission in the (d,t) reaction.

The efficiency ε_α was determined experimentally, for which purpose a ^{238}Pu alpha source of known intensity was installed in place of the Ti-T target. The numerical value of ε_α was $(1.62 \pm 0.03) \times 10^{-6}$. The coefficient R_α was calculated by the method described in Ref. [4] for a deuteron energy of 120 keV and an angle of 171°.

The neutron spectrometer and the procedure for measuring and processing the instrument spectrum are described in more detail in Ref. [12].

The spherical assembly was made of steel with less than 0.3% carbon content. The sphere had an outer diameter of 240 mm and a wall thickness of 75 mm. The assembly was provided with a system of channels for measuring the angular and radial distributions of the reaction rates for iron nuclei and the rates of activation reactions. There was a 62 mm diameter experimental channel along the assembly axis for positioning the neutron generator in the centre of the target. The design of the assembly is shown in Fig. 4.

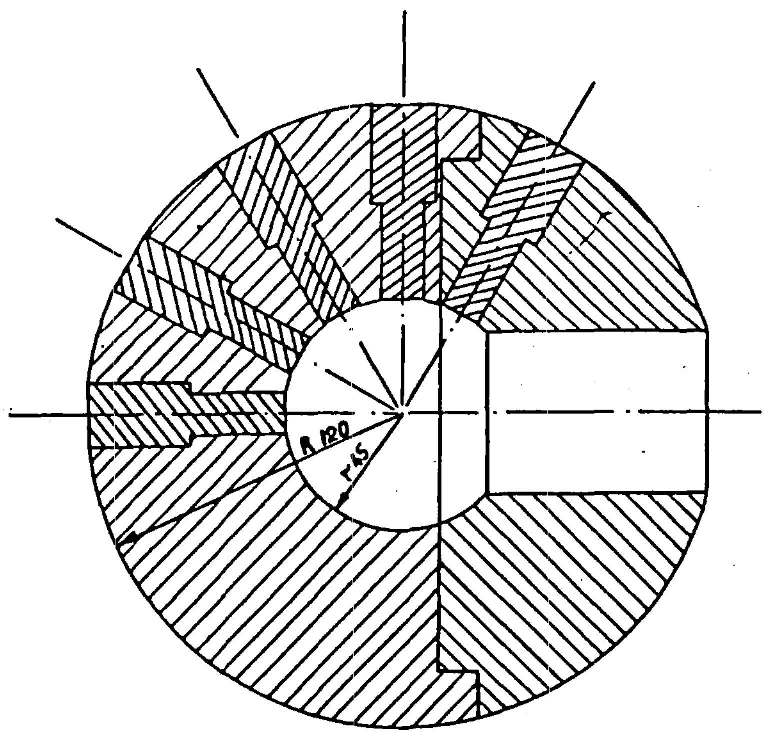


Fig. 4.

Table 5.

Energy region MeV	Experiment
10-15	0.427
5-10	0.050
1-5	0.362
1-15	0.839

Table 6.

Energy Region MeV	Exp.	Calculation					
		BLANK					BRAND
		ENDL75	ENDL83	JENDL	F/B-IV	BROND	ENDL78
1-5	0.362	0.294	0.270	0.323	0.290	0.282	0.241
5-10	0.050	0.044	0.043	0.016	0.038	0.044	0.037
10-15	0.427	0.393	0.393	0.412	0.397	0.422	0.398
1-15	0.839	0.731	0.707	0.752	0.724	0.748	0.676

The energy distribution of neutrons in the 1-15 MeV region was obtained by processing the instrument spectrum by the matrix method used in the FORIST program. The neutron group fluxes are given in Table 5.

The method used for processing the instrument spectra does not give a correct evaluation of the error of the neutron spectrum measured. However, from the extensive practice of utilization of scintillation spectrometers of this type it is known that absolute neutron fluxes can be measured with an error of up to 10% [15]. Some sources of error which occur during the measurement and processing of the instrument spectra of recoil protons are considered in Ref. [12].

4. CALCULATION OF THE NEUTRON LEAKAGE SPECTRUM

In order to compare the experimental results with calculation we used data obtained by the one-dimensional BLANK program and the three-dimensional BRAND program with the ENDL-78 data [13]. The ENDL-75, ENDL-83, JENDL-2, BROND and ENDF/B-IV libraries were used in the calculations by BLANK.

The neutron source in the calculation by the BLANK program is given as an isotropic uniformly distributed point source in the 13.4-14.8 group, corresponding to the energy scatter of neutrons generated in the (d,t) reaction for E_d = 120 keV. Allowance was made for neutron scattering by the structural components of the ion conductor and by the water cooling the target.

By the BRAND program we calculated the spectrum of neutrons emitted at an angle of 0° to the deuteron beam for the actual structure of the target part of the ion conductor. The effect of the experimental channel on the neutron leakage spectrum was evaluated. It was found that at an angle of 0° to the deuteron beam the perturbation of the spectrum in the 1-15 MeV region was within the statistical error of calculation, and therefore the effect of the channel could be ignored. On the basis of this result the effect of the channel can also be neglected in the calculations by the one-dimensional BLANK program.

5. COMPARISON OF EXPERIMENT AND CALCULATION

In Table 6 we compare the leakage neutron fluxes obtained in experiments and those calculated by the BLANK and BRAND programs.

The following conclusions can be drawn from this table:

1. The total flux of source neutrons and elastically scattered neutrons calculated by the various nuclear data versions differs from experiment by not more than 8%. The minimum difference is exhibited by the JENDL-2 and BROND libraries - 3.5 and 1%, respectively. This may be due to the fact that in JENDL-2 and BROND, as compared with ENDL-75, ENDL-83 and ENDF/B-IV, the inelastic scattering cross-sections are lower and, consequently, the elastic scattering cross-sections are higher (see Table 1). As a result, transition of neutrons from the 10-15 MeV region was lower;

2. In the 1-5 MeV region, appreciably more neutrons were recorded in the experiments than in the calculations. The maximum difference in the calculations by BLANK is shown by the ENDL-83 data - about 25%, and the minimum by the JENDL-2 data - less than 11%. These results correlate with the data on the ratio of the partial channels in the inelastic scattering cross-section of these libraries. The σ_{2n}/σ_{in} ratio is smallest for the ENDL-83 library (0.232) and highest for JENDL-2 (0.405). It may be assumed that the latter value is closer to the actual ratio of the reaction cross-sections σ_{2n} and σ_{in}.

   The difference between calculation with the ENDF/B-IV data and experiment is 20%, which agrees with the conclusions of Refs [5, 6] about the scale and nature of the difference between experiment and calculation. The conclusions of Refs [8, 9], where a considerably lower leakage neutron flux was found in the calculation with ENDF/B-IV data, are not confirmed.

   Calculation by the BRAND program with the ENDL-78 data reduces the number of neutrons in the 1-5 MeV region by 33%;

3. Comparison of the leakage neutron fluxes in the 5-10 MeV region also shows that the calculated values are lower than the experimental values, differing by 12-26%. Only in the case of the JENDL-2 data is the difference substantially greater, by more than a factor of 3, which may be attributed to the shape of the emission spectrum used in this library for neutrons generated during inelastic interaction of 14 MeV neutrons with iron nuclei (see Table 2);

4. Comparison of the leakage neutron fluxes in the 1-15 MeV region shows that calculation by the BLANK program with the JENDL-2 data

gives results closest to experiment - a difference of about 10%. The difference between experiment and calculation by the BRAND program (ENDL-78) is substantially greater - as much as 19%.

Making an overall evaluation of the comparison drawn above between the experimental data and the calculation results, we can affirm that for leakage neutron fluxes from an iron sphere the values closest to the measured values are given by the JENDL-2 library. However, the shape of the neutron emission spectrum in this library needs substantial correction.

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