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INFLUENCE OF A PRIORI INFORMATION AND CHOICE OF ACTIVATION DETECTORS IN INTEGRAL EXPERIMENTS ON THE ACCURACY OF NEUTRON SPECTRUM UNFOLDING IN FUSION REACTOR BLANKET MODELS

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INTRODUCTION

In recent years there has been swift development in the new applied branch of neutron physics concerned with the study of the interaction of 14 MeV fusion neutrons (d,t) with prospective fusion reactor blanket materials. Moreover, though at first this research was principally concerned with the measurement of interaction cross-sections and secondary neutron spectra in the reactions (n,2n), (n,3n), (n,f), and (n,n'), nowadays increasing attention is being given to integral experiments. Particularly noticeable is a rise in the importance of integral neutron physics experiments related to design work on the construction of blankets and an evaluation of their engineering and efficiency characteristics. Such macroexperiments enable one to check the accuracy of computing methods and nuclear data used to predict fusion reactor blanket parameters under conditions close to those in actual blankets.

Among the many experimental methods used in integral experiments the activation threshold detector method is fairly widely represented. One may cite such examples as Kuijpers' study of neutron spectra using threshold detectors in a large lithium assembly [1], or F. Tsang's spectrum measurements using a metallic lead assembly [2]. The "Lotus" experiment recently set up (Switzerland, 1984) [3] also involves the extensive use of threshold detectors. Thus it is undoubtedly necessary further to refine methods of threshold detector use. In the first instance this involves the selection for experiments of detectors having the greatest information content.

At first sight this procedure is fairly simple, and usually it consists in choosing detectors whose reaction thresholds uniformly cover the neutron spectrum energy range in question, whose activation cross-sections are sufficiently high, and where the spectra of the gamma rays emitted may be easily unfolded. However, no account is taken here of the peculiarity of neutron spectra in fusion systems where a flux of 14 MeV neutrons from the source is commensurate with, or even in excess of the flux of secondary neutrons from inelastic scattering. The latter are of the greatest interest since they yield information about such reactions as (n,n'), (n,2n), (n,3n) and several others. This peculiarity of this type of spectrum can lead to the detector, even though it has a sufficiently low reaction threshold, being activated principally by the neutrons from the source. As a result, in such experiments one must be particularly careful in one's choice of detectors. Some fairly simple means of selecting activation detectors sensitive to inelastically scattered neutrons are given below.

1. Sensitivity of activation detectors to a flow of inelastically scattered neutrons

If we take the activation integral of an i-th detector, A_i ($A_i = \int_0^\infty \sigma_i(E)\phi(E)dE$, where $\sigma_i(E)$ is the threshold reaction cross-section and $\phi(E)$ is the neutron flux density), to consist of two components, one of which is determined by the neutrons of the source $A_i^{(14)}$, and the other by inelastically scattered neutrons $A_i^{(W)}$:

$$A_i = A_i^{(14)} + A_i^{(W)}$$
$$A_i = A_i^{(14)} + A_i^{(W)} \qquad (1)$$

(For simplicity's sake we will take the elastically scattered neutrons to be identical with the neutrons of the source, which is a good approximation for scattering in the nuclei of heavy elements, for example.)

We then introduce the spectral sensitivity coefficients:

$$K_i^{(W)} = A_i^{(W)}/A_i; \quad K_i^{(14)} = A_i^{(14)}/A_i \qquad (2)$$

Having calculated the values of $K_i^{(W)}$ for the assembly being studied, and

having determined the lowest workable value of this coefficient for the purposes of spectrometry, one may choose suitably sensitive detectors.

In Ref. [4] it is assumed that a detector is suitable if $K_i^{(W)} \geq 0.2$, provided that the error in the measuring of A_i is 10%, i.e. the proportion of secondary neutrons at full reaction rate is at least twice as great as the error level. A decrease in the measurement error leads to decrease in the maximum value of $K_i^{(W)}$.

As an example, the coefficients $K_i^{(W)}$ and $K_i^{(14)}$ were calculated for detectors widely used in experiments, in relation to a spherical uranium assembly with a central source of 14 MeV neutrons. The choice of this material is not coincidental: it is assumed that fusion reactor blankets will use uranium-238 for fusion neutron multiplication. The thickness of the uranium layer in the calculation was taken to be 6 cm, which is about 1.7 times the range of a 14 MeV neutron (this thickness is close to those used in fusion reactor blanket designs). It was assumed that the detectors were located in the centre of the uranium layer. The neutron spectrum was calculated by the BLANK program [5], with the use of neutron constants from the ENDL library [6]. The secondary neutron spectra for the reactions (n,2n), (n,3n) are shown in an evaporation spectrum model. Values for $K_i^{(W)}$ were calculated for the two energy ranges of 0-3 MeV and 0-7 MeV. An energy level of 3 MeV corresponds to the highest limit of the evaporation spectrum of (n,3n) neutrons, and the energy level of 7 MeV to the limit for (n,2n) neutrons. In the evaporation spectrum model one may disregard activation of the detectors by neutrons with an energy of 7-14 MeV (apart from source neutrons). The activation reaction cross-sections were taken from the BOSPOR [7], ZACRSS [8], ENDF/B-V [9], BGS-1 [10] libraries. Table 1 contains the spectral sensitivity coefficients $K_i^{(W)}$ and $K_i^{(14)}$. (The spectral sensitivity coefficient values, except for threshold reactions, are calculated for some (n,γ) reactions and for fission reactions with ^{235}U, ^{239}Pu and ^{241}Am nuclei.)

Table 1

Spectral sensitivity coefficients K_i^W, K_i^{14}

Reaction	K_i^W		K_i^{14}
	Energy interval 0-3 MeV	Energy interval 0-7 MeV	Energy interval 13.7-14.2 MeV
1	2	3	4
1. $^{115}In((n,\gamma)^{116}In$	≈ 1	≈ 1	0
2. $^{63}Cu(n,\gamma)^{64}Cu$	0,80	≈ 1	0
3. $^{45}Sc(n,\gamma)^{46}Sc$	≈ 1	≈ 1	0
4. $^{197}Au(n,\gamma)^{198}Au$	≈ 1	≈ 1	0
5. $^{59}Co(n,\gamma)^{60}Co$	0,95	≈ 1	0
6. $^{23}Na(n,\gamma)^{24}Na$	0,90	≈ 1	0
7. $^{238}U(n,f)$	0,05	0,22	0,73
8. $^{232}Ph(n,f)$	0,02	0,17	0,77
9. $^{239}Pu(n,f)$	0,49	0,68	0,31
10. $^{237}Np(n,f)$	0,43	0,53	0,46
11. $^{235}U(n,f)$	0,45	0,60	0,38
12. $^{241}Am(n,f)$	0,47	0,62	0,35
13. $^{103}Rh(n,n')^{103}Rh$	0,57	0,78	0,19
14. $^{115}In(n,n')^{115}In$	0,47	0,77	0,21
15. $^{47}Ti(n,p)^{47}Sc$	0,04	0,22	0,76
16. $^{58}Ni(n,p)^{58}Co$	0,05	0,26	0,70
17. $^{64}Zn(n,p)^{64}Cu$	0,02	0,18	0,77
18. $^{54}Fe(n,p)^{54}Mn$	0,06	0,24	0,71
19. $^{32}S(n,p)^{32}P$	0,05	0,27	0,69
20. $^{31}P(n,p)^{31}Si$	0,04	0,27	0,68
21. $^{204}Pb(n,n')^{204m}Pb$	0,08	0,28	0,70
22. $^{27}Al(n,p)^{27}Mg$	0	0,07	0,88
23. $^{63}Cu(n,\alpha)^{60}Co$	0	0,01	0,91
24. $^{46}Ti(n,p)^{46}Sc$	0	0,05	0,91
25. $^{35}Cl(n,\alpha)^{32}P$	0,1	0,15	0,81
26. $^{60}Ni(n,p)^{60}Co$	0	0,03	0,90
27. $^{27}Al(n,\alpha)^{24}Na$	0	≈ 0	0,91
28. $^{90}Zr(n,p)^{90}Y$	0	≈ 0	0,95
29. $^{28}Si(n,p)^{28}Al$	0	≈ 0	0,92
30. $^{48}Ti(n,p)^{48}Sc$	0	≈ 0	0,97
31. $^{24}Mg(n,p)^{24}Na$	0	≈ 0	0,95
32. $^{59}Co(n,\alpha)^{56}Mn$	0	≈ 0	0,96
33. $^{232}Th(n,2n)^{231}Th$	0	≈ 0	0,95
34. $^{93}Nb(n,2n)^{92m}Nb$	0	≈ 0	0,97
35. $^{127}I(n,2n)^{126}I$	0	≈ 0	0,97
36. $^{65}Cu(n,2n)^{64}Cu$	0	0	0,98
37. $^{55}Mn(n,2n)^{54}Mn$	0	0	0,97
38. $^{59}Co(n,2n)^{58}Co$	0	0	0,97
39. $^{19}F(n,2n)^{18}F$	0	0	0,98
40. $^{63}Cu(n,2n)^{62}Cu$	0	0	0,98
41. $^{90}Zr(n,2n)^{89}Zr$	0	0	0,98
42. $^{58}Ni(n,2n)^{57}Ni$	0	0	0,99
43. $^{23}Na(n,2n)^{22}Na$	0	0	0,98

It follows from Table 1 that for secondary neutron spectrometry (we are giving the term spectrometry a wider meaning here, including an evaluation of spectral shape based on activation integral values) in a uranium assembly, less than half of the detectors examined were suitable. It is interesting that such widely used detectors as $^{27}Al(n,\alpha)$ and (n,p), $^{24}Mg(n,p)$, $^{54}Fe(n,p)$ and several others proved inacceptable.

High sensitivity to secondary neutrons is displayed by (n,γ) detectors which register practically no source neutrons. However, it is well known that one must be cautious in using (n,γ) detectors because of their high sensitivity to the background neutrons present in any neutron experiments. Irradiation of these detectors through a cadmium or boron filter significantly decreases this problem.

Thus a choice of detectors according to $K_i^{(W)}$ coefficient values is entirely sufficient for experiments on measuring the integrated flux of inelastically scattered neutrons. Hence $K_i^{(W)}$ is an indispensable indicator of the usefulness of an i-th detector for neutron spectrometry. However, a high sensitivity to neutron flux by no means indicates a sensitivity to their energy distribution shape. For instance, a detector whose activation cross-section is determined by the following conditions:

$$\sigma_i(E) = \text{const}, \quad \text{where } 0 \leq E < 14 \text{ MeV}$$

$$\sigma_i(E) = 0, \quad \text{where } E \geq 14 \text{ MeV},$$

registers no source neutrons at all, although such a detector is totally insensitive to a change in neutron spectral shape since

$$A_i = \int_0^{E<14\,MeV} \sigma_i(E)\varphi(E)dE = \sigma_i \int_0^{E<14\,MeV} \varphi(E)dE = \sigma_i \cdot \Phi,$$

where Φ is the integrated flux. Thus the next stage of detector choice is detector selection according to sensitivity to neutron spectral shape.

2. Sensitivity of detectors to neutron spectral shape

The capacity of a detector to respond to a change in a neutron spectrum can be characterized by using the sensitivity coefficient:

$$\gamma_{ij} = \frac{\partial \ln A_i}{\partial \ln C_j} \quad . \tag{3}$$

where A_i is the activation integral of the i-th detector; C_j is one of the parameters determining the neutron field of the assembly. For instance, if secondary neutrons are represented in the evaporation spectrum model, sensitivity to spectral shape can be defined by using the effective spectrum temperature for C_j. Expression (3) is widely used in reactor calculations to evaluate the sensitivity of various functionals to nuclear data.

The lowest level of values permissible for γ_{ij} can be determined in the following manner. Let $\overline{\Delta C}_j$ be the confidence interval of variation in the parameter C_j whose mean value is $\overline{C}_j$. The correction of $\overline{C}_j$ within this confidence interval corresponds to the error margin $\Delta A_i = A_i$ calc. $(\overline{C}_j) - A_i$ exp., which is equal to

$$\Delta A_i = A_{i,\,calc.}(\bar{C}_j) \cdot \gamma_{ij} \frac{\overline{\Delta C_j}}{\bar{C}_j} \tag{4}$$

Obviously, the experimental value of A_i will be helpful in correcting $\overline{C}_j$ if the $\delta A_{i\ exp.}$ error is less than this value. Hence the lowest permissible value for γ_{ij} is given by the expression:

$$\gamma_{ij} \geq \frac{\overline{C_j}}{\overline{\Delta C_j}} \cdot \frac{\delta A_{i\,exp.}}{A_i} \tag{5}$$

The measurement error of activation integrals in 14 MeV neutron sources usually does not exceed 10%. For parameters of C_j such as, for instance, the temperature of the neutron evaporation spectrum, the relation $\overline{\Delta C}_j/\overline{C}_j$ can reach values of ~ 0.5 (a similar spread of $T_{eff.}$ for some heavy elements is given in Ref. [11]). Therefore the limit of γ_{ij} is given by the expression:

$$\gamma_{ij} \geq 0.2 \tag{6}$$

As an example of this method of choosing detectors according to their sensitivity to spectral form, in Table 2 values of γ_{ij} are given for the uranium-238 assembly described above. Calculation of γ_{ij} coefficients by the direct use of standard computer programs is complicated by the fact that these programs are rigidly orientated around the use of a specific library of nuclear data. Therefore, to calculate sensitivity coefficients, a model spectrum was used similar to the spectrum of the uranium assembly and readily variable.

Let us introduce a_j - the probability of the j-th multiplication process in an assembly, induced by the source neutrons. Disregarding second generation neutron multiplication (which is permissible for small-size assemblies), we may write the following expression for an assembly-volume-averaged model spectrum:

$$\bar{\Phi}(E) = \text{const}[\delta(E-E_{source}) + \sum_j \nu_j a_j \phi_j(E)] \qquad (7)$$

where $\phi_j(E)$ is the secondary neutron energy distribution of the j-th reaction, so that $\int_0^\infty \phi_j(E)dE = 1$; and where ν_j is the neutron yield per single event of the j-th reaction.

With this representation of the spectrum under study, its shape can be easily varied. To describe the spectra for (n,2n) and (n,3n) reactions an evaporation spectrum model was used. A fission neutron spectrum was approximated by a Maxwellian spectrum with temperature $T_{eff.} = 1.5$ MeV [12]. The a_j reaction probabilities were calculated by means of the BLANK program and the values of $T_{(n,2n)}$ and $T_{(n,3n)}$ were taken from the ENDL library.

The γ_{ij} coefficients were found by direct calculation, replacing the derivative by its finite-difference analog. The error due to such a substitution is insignificant where the argument change is within 10%. Table 2 gives the results of calculations of γ_{ij} coefficients against temperature for neutron spectra in (n,2n), (n,3n) and (n,f) reactions with uranium-238 nuclei for a number of activation detectors (the detectors had already been chosen according to the values of the coefficients $K_i^{(W)}$).

Table 2

	Reaction	$\gamma_{(n,3n)}$	$\gamma_{(n,2n)}$	$\gamma_{(n,f)}$
I.	$^{115}In(n,\gamma)$	-0,04	-0,10	-0,30
2.	$^{197}Au(n,\gamma)$	-0,13	-0,14	-0,35
3.	$^{63}Cu(n,\gamma)$	-0,08	-0,09	-0,26
4.	$^{115}In(n,n')$	0,12	0,15	0,33
5.	$^{103}Rh(n,n')$	0,08	0,09	0,23
6.	$^{239}Pu(n,f)$	0,01	0,01	0,02
7.	$^{237}Np(n,f)$	0,04	0,03	0,08
8.	$^{238}U(n,f)$	0,04	0,06	0,18
9.	$^{31}P(n,p)$	0,05	0,13	0,37
10.	$^{32}S(n,p)$	0,03	0,11	0,33
11.	$^{58}Ni(n,p)$	0,03	0,10	0,35
12.	$^{54}Fe(n,p)$	0,02	0,10	0,36
13.	$^{47}Ti(n,p)$	0,02	0,07	0,22
14.	$^{64}Zn(n,p)$	0,02	0,08	0,28

The table shows that some detectors respond very weakly to variation in secondary neutron spectral shape. For instance, where there is a 10% change in the temperature of the fission neutron spectrum of uranium-238, the rate of the (n,f) reaction in plutonium-239 changes by only 0.2%. The detectors in Table 1 which do not appear in Table 2 have even smaller values of γ_{ij} and, consequently, do not satisfy criterion (5).

Thus the use of the coefficients $K_i^{(W)}$ and γ_{ij} has enabled us to rule out less sensitive, and therefore experimentally unsuitable, detectors.

3. The influence of the choice of activation detectors on analysis results

Let us consider what results an insufficiently substantiated choice of detectors may have for an integral experiment with a 14 MeV neutron source. Here we shall use Kuijpers' experiment [1], which was conducted on a large metallic lithium assembly, as an example. In this experiment activation reaction rates were measured at three points of the apparatus: at a point within the immediate vicinity of the source, at the centre of the cylindrical lithium layer and on the outer surface of the assembly, and then a

Table 3

Spectral sensitivity coefficients (%) K_i^W for the Kuijpers' results [1]

Reaction	R, cm (distance from centre of assembly)		
	10	30.8	52.8
$^{58}Ni(n,2n)^{57}Ni$	0	0	0
$^{19}F(n,2n)^{18}F$	0	0	0
$^{127}I(n,2n)^{126}I$	0	31,3	49,2
$^{197}Au(n,2n)^{196}Au$	0,8	32,9	47,9
$^{63}Cu(n,2n)^{62}Cu$	2,1	10,9	17,6
$^{63}Cu(n,\gamma)^{64}Cu$	0	35,8	64,8
$^{59}Co(n,\alpha)^{56}Mn$	1,6	44,8	58,6
$^{24}Mg(n,p)^{24}Na$	1,8	41,6	59,8
$^{56}Fe(n,p)^{56}Mn$	2,3	37,3	58,2
$^{27}Al(n,\alpha)^{24}Na$	5,0	40,4	61,4
$^{64}Zn(n,p)^{64}Cu$	6,7	63,3	79,7
$^{58}Ni(n,p)^{58}Co$	7,7	68,8	82,6
$^{55}Mn(n,\gamma)^{56}Mn$	7,5	84,4	96,0
$^{27}Al(n,p)^{27}Mg$	8,0	56,6	75,1
$^{115}In(n,\gamma)^{116}In$	25,3	90,0	97,4
$^{115}In(n,n')^{115m}In$	31,6	87,9	92,2

differential neutron spectrum was unfolded by means of the SAND-II programs [13, 14].

If, for the lithium assembly spectrum, we calculate the values of the spectral sensitivity coefficients $K_i^{(W)}$ (see Table 3), we can see that, at the first sampling point, the secondary neutron contribution exceeds the measurement error only in the case of two detectors (in Ref. [1] the measurement error was estimated to be 15%). The remaining 14 detectors give information only about the source neutrons. Therefore, the unfolding of the neutron spectrum was based on only two detectors. From the example given it is obvious that the choice of detectors in Ref. [1] cannot be considered successful, at least for the first sampling point.

Let us see how the accuracy of the neutron spectrum unfolding would be effected by adding in to Kuijpers' choice of detectors those recommended in

this paper. For these purposes the following computer-simulated experiment was conducted. The following detectors were added into Kuijpers' selection: $^{235}U(n,f)$, $^{239}Pu(n,f)$, $^{103}Rh(n,n')$, $^{237}Np(n,f)$ and $^{241}Am(n,f)$. (These detectors were chosen on the basis of their K_i^W values, their activation reaction rates having been calculated for a spectrum generated by the MORSE program for a metallic lithium assembly.) By means of a random number generator, a normal error distribution with a standard deviation of 5% was superimposed on the activation reaction rates calculated for the first sampling point. For each detector 30 reaction rate values were calculated. Thus, 30.n (where n is the number of detectors) activation reaction rate variants were generated. The SAND-II program was used to unfold the spectrum.

In Table 4 the results of a comparison of the test spectrum and the spectrum unfolded using the two selections of activation detectors, Kuijpers' and our own, are given.

The comparison was conducted using the following expressions:

$$\Delta\varphi(E) = \frac{\bar{\varphi}(E) - \varphi^{T}(E)}{\varphi^{T}(E)} \cdot 100\%$$

where: $$\bar{\varphi}(E) = \frac{\sum_{i=1}^{N} \varphi_i(E)}{N}$$

$\phi^{T}(E)$ is the test spectrum calculated for a lithium assembly using the MORSE program;

$N = 30 \cdot n$ is the number of spectrum unfolding variants;

$\phi_i(E)$ is the results of the various unfolding variants.

$$\delta\varphi(E) = \left\{ \sqrt{\sum_{i=1}^{N} \frac{[\bar{\varphi}(E) - \varphi_i(E)]^2}{N}} \Big/ \bar{\varphi}(E) \right\} \cdot 100\%$$

The results received confirm our recommendations on the choice of detectors with the greatest information content. By adding to Kuijpers' choice of 16 detectors only five of the detectors recommended by us, the discrepancies between the test spectrum and the unfolded spectrum were reduced by a factor of 5-10.

Table 4

Comparison of the results of the unfolding of a neutron spectrum in a lithium assembly

Energy interval (MeV)	Kuijpers' choice of detectors		Extended detector choice	
	$\Delta\varphi(E)$, %	$\delta\varphi(E)$, %	$\Delta\varphi(E)$, %	$\delta\varphi(E)$, %
1	2	3	4	5
0,1 - 0,2	12,6	64,8	-0,13	13,5
0,5 - 0,6	1,8	20,5	0,24	9,9
1,0 - 1,1	34,5	19,7	0,38	10,2
2,0 - 2,1	23,1	15,5	0,28	8,8
3,0 - 3,1	-13,1	11,0	0,36	8,1
4,0 - 4,1	-19,4	12,4	0,4	8,6
5,0 - 5,1	-10,8	11,4	0,2	8,3
6,0 - 6,1	-20,0	11,5	0,03	8,5
7,0 - 7,1	- 4,7	8,7	-0,12	6,5
8,0 - 8,1	-12,3	6,9	-0,27	5,4
9,0 - 9,1	- 7,3	7,0	-0,28	5,6
10,0 - 10,1	7,0	6,9	0,3	5,5
11,0 - 11,1	9,6	7,3	-0,2	6,3
12,0 - 12,1	43,0	6,7	-0,12	6,2
13,0 - 13,1	19,1	5,3	0,05	5,0
14,0 - 14,1	- 5,2	3,4	0,11	3,2

5. Conclusions

Thus the selection criteria proposed permit the choice of suitably sensitive activation detectors for the purposes of inelastically scattered neutron spectrometry. These activation detectors can be used in fairly small-scale assemblies (≃ 14 MeV neutron range up to inelastic interaction), or at short distances from the source in large-scale assemblies. Obviously, the selection of detectors at the planning stage of an experiment avoids the use of detectors with a low information content and duplicate detectors etc. The influence of detector choice on the quality of the unfolding of the neutron spectrum is especially striking. The reduction in the number of detectors used in an experiment significantly reduces the data-gathering period and makes it less expensive.

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Influence of a priori information on the accuracy of "thermonuclear" neutron spectrum unfolding

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1. Introduction

It is well known that neutron spectrum unfolding by means of measured activation reaction rates requires additional a priori information in the form of a starting spectrum [1-4]. This information may be obtained by neutron physics calculation or taken from direct measurements of the spectrum in a facility with similar characteristics. The aim of unfolding should therefore be to improve our understanding of the neutron spectrum under study with the aid of measured activation reaction rates. In this context, it is important to establish the extent to which the difference between the a priori and the desired neutron spectrum affects the accuracy of unfolding.

The results of research on the sensitivity of the unfolded neutron spectrum to the accuracy of a priori information appear below. The problem is solved using the example of spectra that are characteristic for thermonuclear systems. Unfolding is carried out with the help of the SAND-II program [5], which is incorporated along with the working cross-section library and service program in the SAIPS computer system. The set of activation detectors for unfolding the "thermonuclear" spectra was chosen on the basis of data from Refs [7, 8].

2. Model spectrum of thermonuclear neutrons

The energy distribution of neutrons is considerably "harder" in the blanket of a thermonuclear reactor than in the core of a fission reactor owing to the high energies of deuterium and tritium fusion neutrons. The presence in the spectrum of so strong an inhomogeneity as the line of 14 MeV monoenergetic source neutrons complicates the task of unfolding and raises the

requirements for a priori spectrum accuracy. Hence, in investigating the influence of the a priori spectrum on unfolding accuracy, the fraction of 14 MeV neutrons in the total flux should be varied over a broad range.

By convention, the thermonuclear neutron spectrum may be represented as consisting of two components: the 14 MeV monoenergetic fusion neutrons and the secondary neutrons generated in the inelastic reactions (n,'n), (n,2n), (n,3n) or (n,f).

For simplicity's sake, the source neutrons which have undergone elastic scattering may be regarded as 14 MeV neutrons. Such an assumption corresponds fairly accurately to the actual situation in a number of distinct cases, e.g. in scattering on heavy elements. The ratio of 14 MeV to secondary neutrons in the total flux is a function of the distance to the first wall and rapidly declines as that distance increases.

Inelastically scattered neutrons may be described by the following evaporation spectrum:

$$\varphi(E) = (E/T_{eff}^2) \cdot \exp(-E/T_{eff}) \qquad (1)$$

where T_{eff} is the effective nuclear temperature depending on the type of nucleus and the initial neutron energy. By varying the value of T_{eff} it is possible to alter the shape of the evaporation spectrum within broad limits.

The 14 MeV source neutron spectrum is conveniently described as a normal distribution:

$$\varphi'(E) = \left(1/\sqrt{2\pi}\,\sigma\right) \cdot exp\left[-\frac{(E-E_o)^2}{2\sigma^2}\right] \qquad (2)$$

where E_o = 14.1 MeV, and σ is the width of the source line at half height. If σ is taken to be equal to 0.2–0.3 MeV, then the distribution will correspond closely enough to the neutron spectrum generated by the (d,t) reaction with E_d = 100–150 keV.

Using these assumptions, a model thermonuclear neutron spectrum can readily be created displaying the basic characteristics of its shape. Varying the ratio of the 14 MeV neutrons and the evaporation spectrum makes it

possible to imitate the change in the spectrum across the thickness of the blanket.

Clearly, such a neutron spectrum does not reflect all the wide variety of processes contributing to the formation of the neutron energy distribution in the actual material of a thermonuclear reactor blanket; it simply provides an approximate picture, but that is perfectly adequate for the purposes of this work.

3. Definition of the problem

Using model neutron spectra, we can evaluate the effect of physically substantiated a priori information on unfolding accuracy. Let us conduct the following numerical experiment. By varying the value of T_{eff} in Eq. (1), we can obtain a set of model spectra $\{\varphi(E)\}_j$. The range of variation of T_{eff} cannot be arbitrary, but must correspond to the credible range of effective temperature values, which is known from differential experiments. Let us choose, as an a priori spectrum, the spectrum with a temperature corresponding to the mean value of T_{eff} in the given temperature range - $\bar{T}_{eff}$. The activation reaction rates we shall calculate on the basis of the remaining spectra:

$$A_{ij} = \int \sigma_i(E) \cdot \varphi_j(E) dE \qquad (3)$$

where i = 1,2...N, and N is the number of detectors.

Let us unfold the neutron spectra φ_j^{unf} with respect to the j-sets of activation integrals A_{ij}, using as an a priori spectrum the same spectrum with a temperature $\bar{T}_{eff}$. By comparing $\varphi_j^{unf}(E)$ and $\varphi_j(E)$, we can determine the sensitivity of the unfolded spectrum to a priori information.

The results of the neutron spectrum unfolding as a function of two parameters (T_{eff} and Q - the fraction of source neutrons in the total flux) are given below.

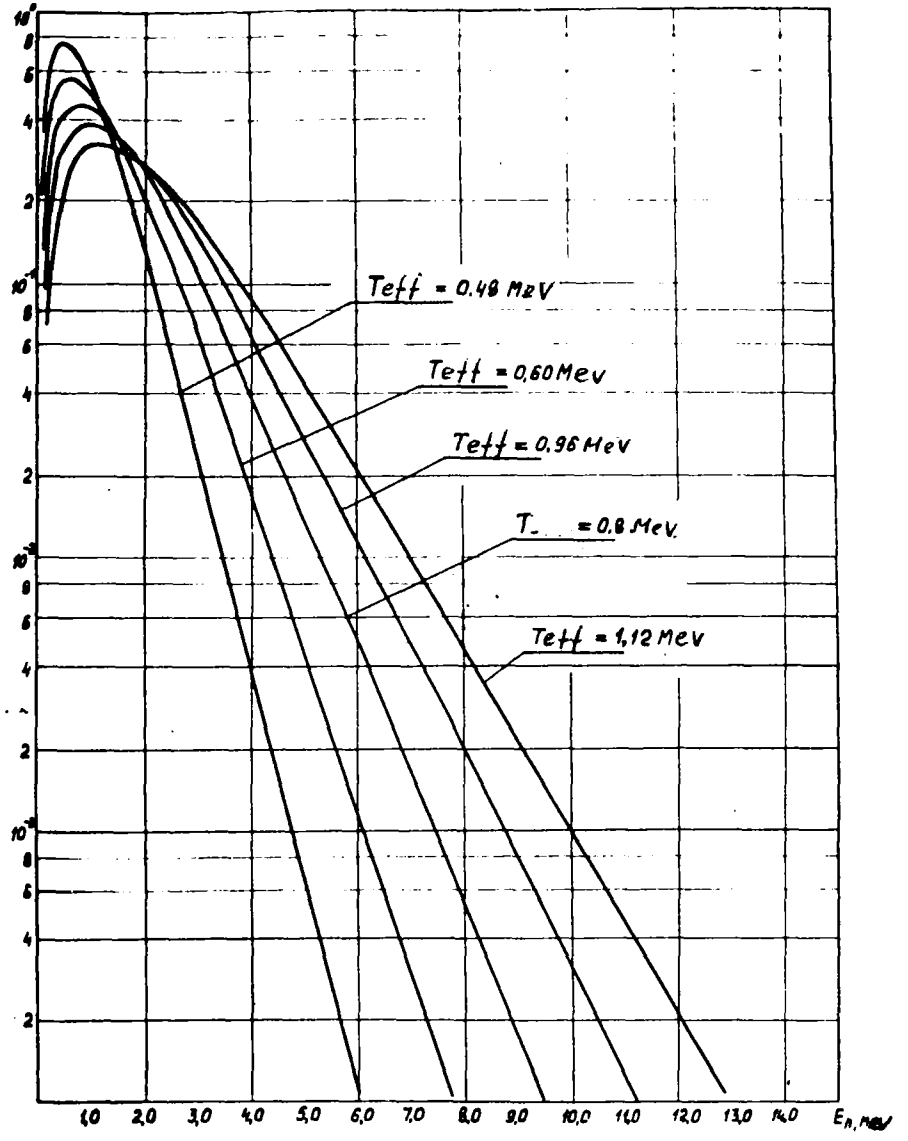
Teff = 0.48 MeV
Teff = 0,60 MeV
Teff = 0,96 MeV
T_ = 0,8 MeV
Teff = 1,12 MeV
1,0 2,0 3,0 4,0 5,0 6,0 7,0 8,0 9,0 10,0 11,0 12,0 13,0 14,0
E_n, MeV

Fig. 1

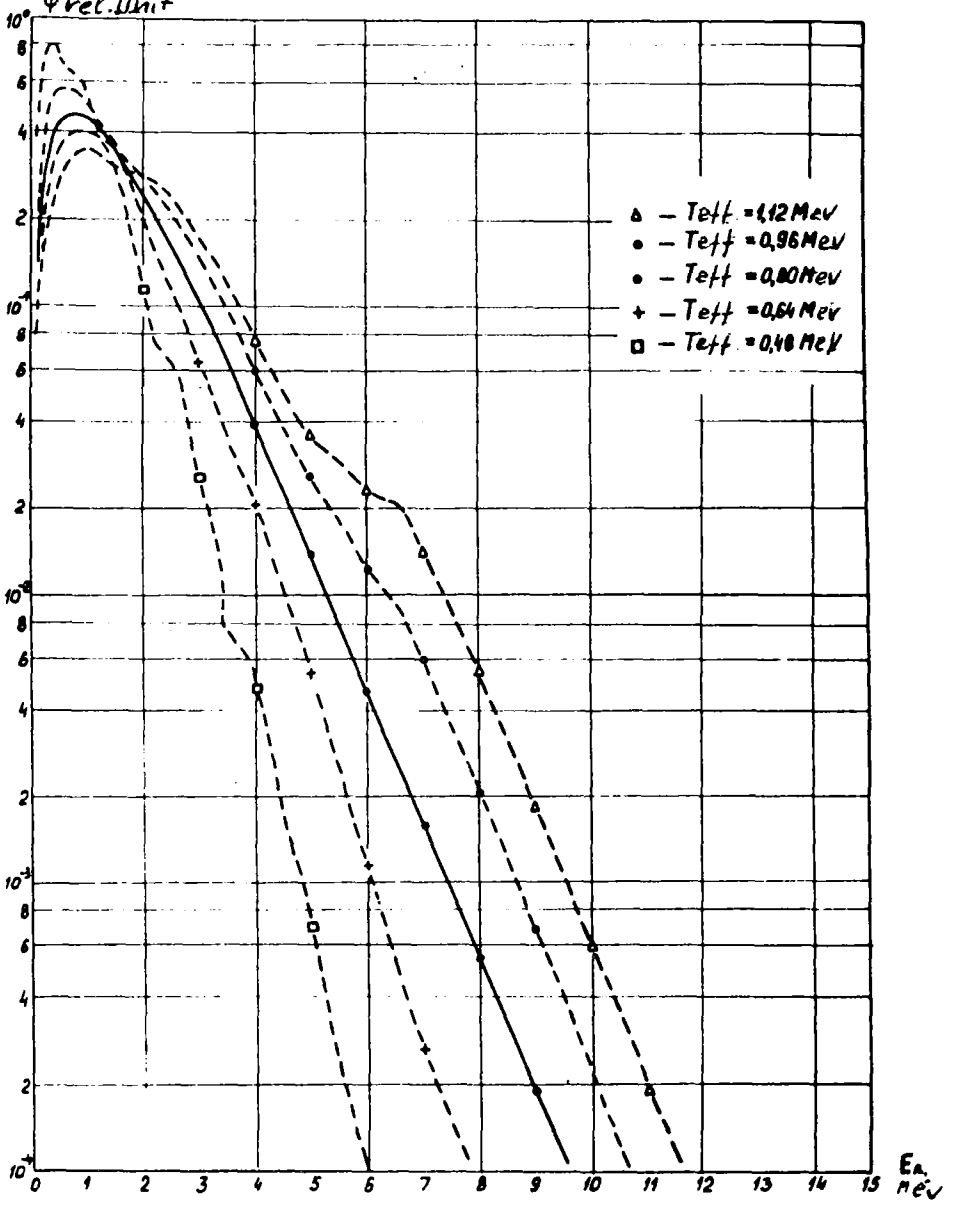
Φ rel. unit
Δ — Teff = 1,12 MeV
• — Teff = 0,96 MeV
• — Teff = 0,80 MeV
+ — Teff = 0,64 MeV
□ — Teff = 0,48 MeV
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
E_n, MeV

Fig. 2

4. Calculation results

(a) Q = 0

An evaporation spectrum was often unfolded in which the fraction of 14 MeV neutrons was negligible. The spectrum of neutrons from the reaction Pb(n,2n) for an initial neutron energy of 14.1 MeV was taken as an example. In accordance with the data in Ref. [9], the effective temperature which satisfies this energy distribution is approximately 0.8 MeV. The spread in this value according to various authors is about ± 40%. We calculated evaporation spectra for effective temperatures T_{eff} of 0.48 MeV, 0.64 MeV, 0.8 MeV, 0.96 MeV and 1.12 MeV, i.e. over the range 0.8 MeV ± 40%. These spectra are shown in Fig. 1. The temperature of the a priori spectrum T_{apr} is taken to be 0.8 MeV.

Unfolding took place in the energy range 0.1-15 MeV. The activation integrals were calculated by group approximation of the activation reaction cross-sections:

$$A_i = \sum_{k=1}^{150} \sigma_k^i \cdot \varphi_k \cdot \Delta E_k \qquad (4)$$

The values of A_i were calculated for the following reactions: (n,γ) for the isotopes ^{63}Cu, ^{115}In and ^{197}Au; (n,p) for ^{27}Al, ^{28}Si, ^{31}P, ^{32}S, ^{24}Mg, ^{47}Ti, ^{54}Fe, ^{56}Fe, ^{58}Ni and ^{64}Zn; (n,α) for ^{27}Al; (n,f) for ^{237}Np, ^{238}U and ^{239}Pu. The unfolding made use of the precise values of the activation integrals. The results appear in Fig. 2.

As quantitative characteristics of the difference between the spectra we used the values: $\varphi^{unf}(E)/\varphi(E)$ and $\overline{\delta\varphi}$ - the weighted-average deviation determined from the following expressions:

$$\overline{\delta\varphi} = \frac{\delta\varphi_1 \cdot \omega_1 + \delta\varphi_2 \cdot \omega_2 + \ldots + \delta\varphi_n \cdot \omega_n}{\omega_1 + \omega_2 + \ldots + \omega_n} \qquad (5)$$

$$\delta\varphi_i = \frac{\varphi(E_i) - \varphi^{unf}(E_i)}{\varphi(E_i)} \qquad i = 1, \ldots n \qquad (6)$$

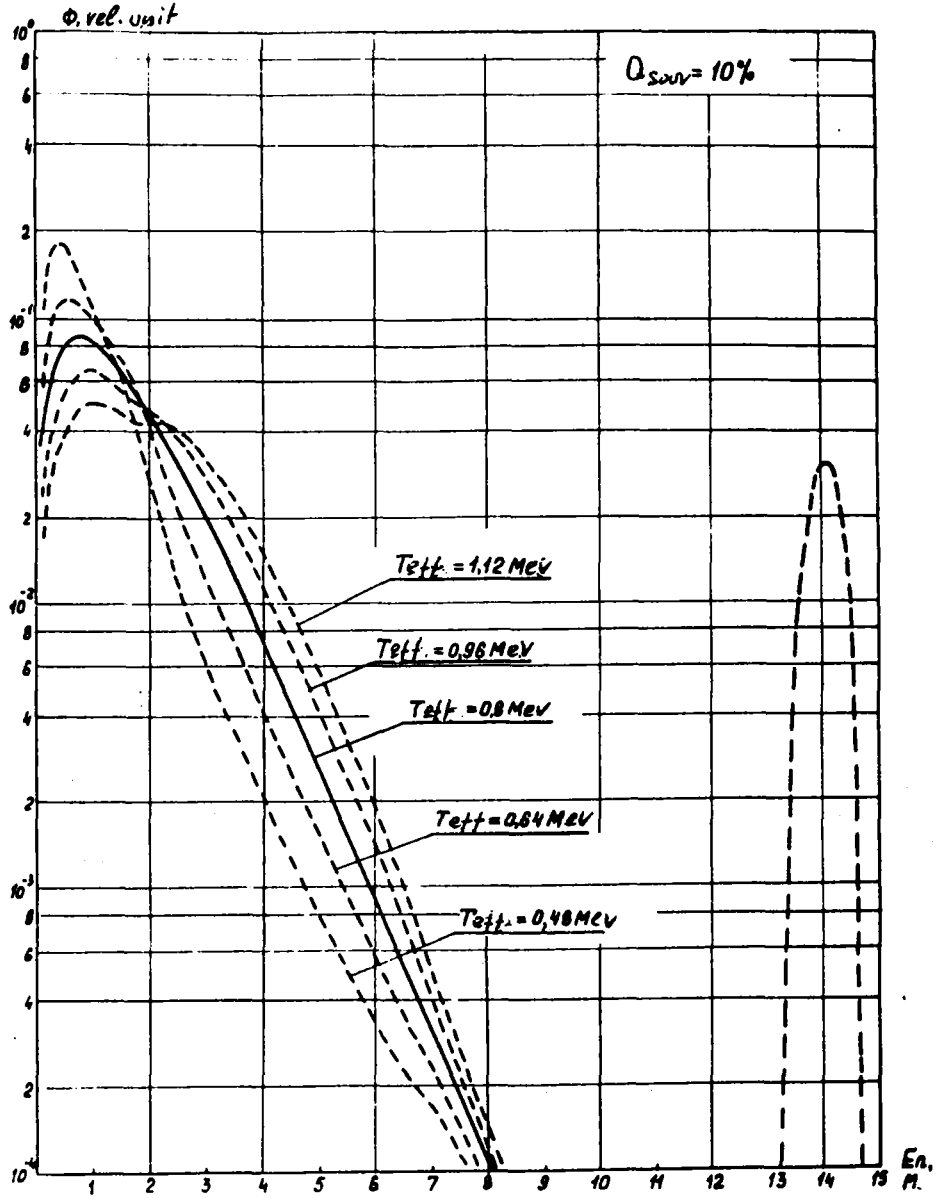
Φ, rel. unit
Q sour = 10%
Teff. = 1,12 MeV
Teff. = 0,96 MeV
Teff. = 0,8 MeV
Teff = 0,64 MeV
Teff. = 0,48 MeV
En. M.

Fig. 3

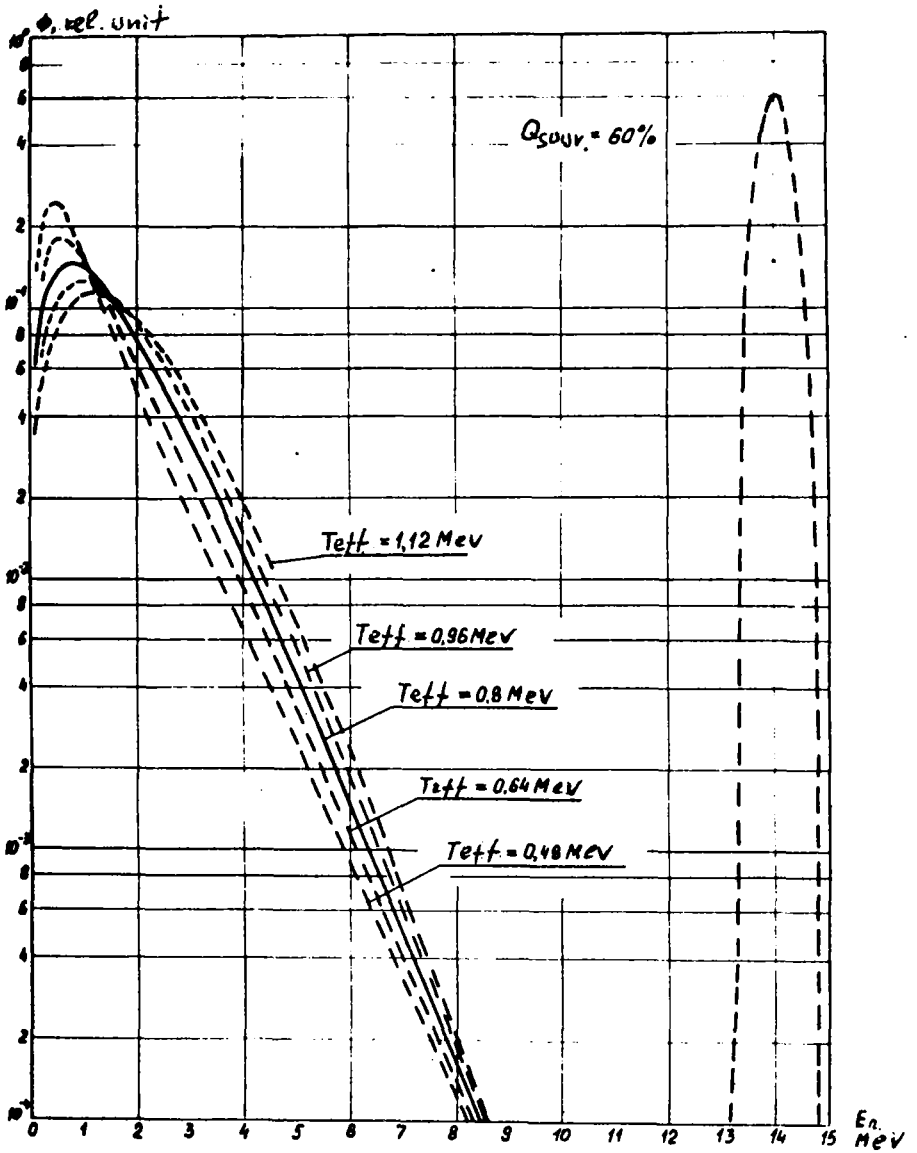
Φ, rel. unit
Q sour. = 60%
Teff = 1,12 MeV
Teff = 0,96 MeV
Teff = 0,8 MeV
Teff = 0,64 MeV
Teff = 0,48 MeV
En. MeV

Fig. 4

$$\omega_i = \frac{\varphi(E_i)\cdot\Delta E_i}{\sum_{i=1}^{n}\varphi(E_i)\Delta E_i} \qquad i = 1,\ldots..n \tag{7}$$

Comparison of the desired and unfolded spectra shows their proximity, even for those cases in which T_{eff} and T_{apr} differ by 40%.

Over a broad range of energies the value of $\varphi^{unf}(E)/\varphi(E)$ did not deviate from unity by more than 10-15%. The difference in the fluxes increases as neutron energy increases. In certain cases with high energies ($E_n \gtrsim 10$ MeV, $T_{eff} = 1.12$ MeV), it may reach about 100%. However, the neutron fluxes for the given energies are so small that their contribution to the total flux $\phi(E) = \int_E \varphi(E)dE$ may be neglected. This circumstance is corroborated by the fact that, as can be seen in Table 1, the weighted-average deviation $\overline{\delta\varphi}$ does not exceed 5%.

Table 1

Weighted-average deviation of unfolded and desired spectra for various T_{eff}

T_{eff}	0.48 MeV	0.64 MeV	0.96 MeV	1.12 MeV
$\overline{\delta\varphi}$	4.62×10^{-2}	2.68×10^{-2}	3.15×10^{-2}	4.28×10^{-2}

Hence, in the case of a smooth evaporation spectrum, even an appreciable error in our knowledge of the a priori spectrum will be "corrected" with the help of measured reaction rates.

(b) $Q > 0$

The 14 MeV neutron fraction in the total flux Q was varied between 10 and 60%, and the temperatures of the evaporation part, as in the previous case, were 0.48 MeV, 0.64 MeV, 0.80 MeV, 0.96 MeV and 1.12 MeV. The spectrum for which $T_{apr} = 0.8$ MeV was taken as the a priori spectrum, and the fraction of source neutrons matched the corresponding value in the desired spectrum.

Figures 3 and 4 show several unfolding results. Considerable distortion of the evaporation part of the neutron spectrum is observed. The

difference between the desired and the unfolded spectrum grows with increasing neutron energy. At high energies, the unfolded spectra have a tendency to converge with the a priori spectrum. This is particularly noticeable in Fig. 4, which shows spectra with Q = 60%.

Hence, the difference between the unfolded and desired spectra and the fraction of source neutrons Q in the total flux $\phi(E)$ are directly related. In any event, for neutrons with energies of more than 2-3 MeV, the relationship can be clearly discerned: the smaller the fraction of source neutrons in the total flux, the smaller the difference between the spectra being compared. This is shown clearly in Fig. 5. It can be seen that the unfolded and desired spectra differ little (within 10%) up to an energy of ~ 2 MeV, above which there is a rapid divergence between $\varphi^{unf}(E)$ and $\varphi(E)$.

The second important circumstance is that the magnitude of the difference between the spectra depends strongly upon $\Delta T = T_{eff} - T_{apr}$. This difference is particularly great when $T_{eff} = 0.48$ MeV. The decrease in the effect of the value of Q on the deviation of $\varphi^{unf}(E)$ from $\varphi(E)$ is noticeable when neutron energy increases.

Special mention should be made of the unfolding of a spectrum whose evaporation-part temperature is 0.8 MeV, which is the same as the temperature in the a priori spectrum. The unfolded and desired spectra were virtually identical for all fractions of source neutrons. The maximum difference did not exceed 20% for neutrons with an energy of 13 MeV.

Despite the considerable difference in the fluxes $\varphi^{unf}(E)$ and $\varphi(E)$, the weighted-average deviation of the spectra proved to be insignificant. Tables 2 and 3 show the values of $\overline{\delta\varphi}$ for various temperatures T_{eff} and source neutron fractions in the total flux.

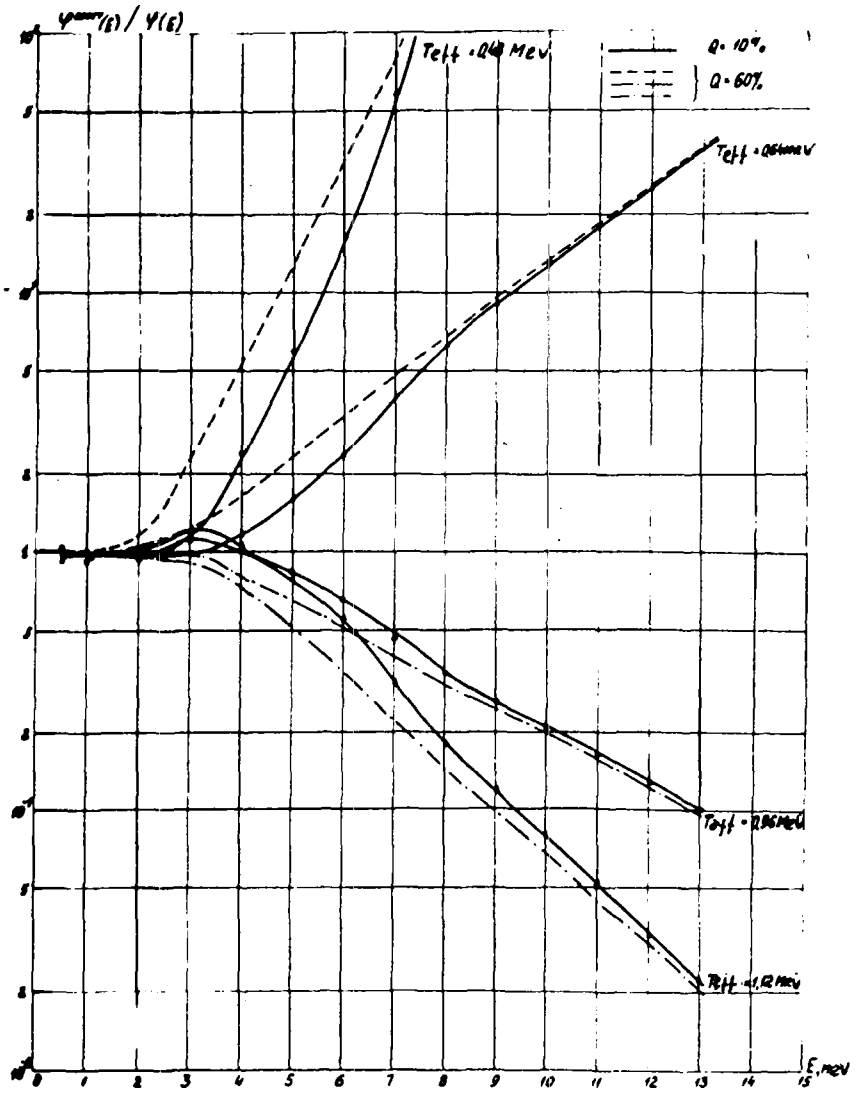

Fig. 5

Table 2

Weighted-average deviation of spectra for Q = 60%

Energy range ΔE, MeV	T_{eff} 0.48 MeV	0.64 MeV	0.96 MeV	1.12 MeV
0.1-15	6.24×10^{-2}	3.42×10^{-2}	3.54×10^{-2}	7.07×10^{-2}

Table 3

Weighted-average deviation of spectra as a function of the fraction of source neutrons Q in the total flux for T_{eff} = 0.48 MeV

Energy range ΔE, MeV	Q 10%	20%	40%	60%
0.1-15	6.03×10^{-2}	8.77×10^{-2}	8.45×10^{-2}	6.24×10^{-2}

It is interesting to note that the weighted-average deviation is virtually independent of Q, and that $\overline{\delta\varphi}$ itself is less than 10%. At the same time, the sensitivity of $\overline{\delta\varphi}$ to ΔT is notable.

(c) Taking the measurement error of activation integrals into account

In the preceding sections, spectrum unfolding was performed using precise values of the activation integrals. Owing to the incorrect statement of the unfolding problem however, the presence of an error ΔA_i in the activation integrals may have a considerable effect on the results of spectrum unfolding.

In our work the activation integral error was modelled as follows: an error of $\pm \Delta A_i$ was "assigned" in a statistically independent manner to each activation integral. The number of these random selections, n = 10. The activation integral error was taken to equal 5 or 10%. If the number of activation detectors is N, then (n • N) sets of activation integrals are obtained for unfolding m = (n • N) neutron spectra. The set of unfolded spectra was used to calculate the mean value of the neutron flux with an energy (E):

$$\overline{\varphi(E)} = \frac{\sum_{\kappa=1}^{m} \varphi_\kappa(E)}{m} \tag{8}$$

where $\varphi_k(E)$ is the flux of neturons with energy E in a spectrum unfolded using the results of the k-th assignment of error.

The maxiumum deviation of the unfolded spectra from the mean value (the dispersion) was determined using the expression:

$$\overline{\Delta\varphi(E)} = \frac{\overline{\varphi}(E) - \max\{\varphi_\kappa(E)\}}{\overline{\varphi}} \cdot 100\ \% \tag{9}$$

The accuracy of unfolding was evaluated on the basis of the weighted-average deviation $\overline{\delta\varphi}$, the spectrum $\overline{\varphi(E)}$ being taken as the unfolded spectrum. Table 4 shows the values of $\overline{\delta\varphi}$ for the neutron evaporation spectrum when the activation integral measurement error $\Delta A_i = \pm$ 10%.

Table 4

Weighted-average deviation $\overline{\delta\varphi}$ for the evaporation spectrum; $\Delta A_i = \pm 10\%$

T_{eff}	0.48 MeV	0.64 MeV	0.80 MeV	0.96 MeV	1.12 MeV
$\overline{\delta\varphi}$	8.14×10^{-2}	5.85×10^{-2}	1.63×10^{-2}	4.07×10^{-2}	6.94×10^{-2}

A comparison of Tables 1 and 4 shows that a 10% activation integral error almost doubles the unfolding error. For example, for a spectrum temperature of 0.48 MeV the value of $\overline{\delta\varphi}$ increased from 4.62% to 8.14%. An unfolding error was found for the spectrum with T_{eff} = 0.8 MeV taken as the a priori spectrum, but this error was not great, amounting to 1.63%.

An increase in the weighted-average deviation is observed only in the 4-5 MeV region, where the neutron contribution to A_i is considerable. In the energy region above 5 MeV, the values of $\overline{\delta\varphi}(E)$ (the weighted-average deviation was calculated in an energy group with a width ΔE = 1 MeV) did not change, i.e. introducing an error into A_i does not affect unfolding accuracy in this part of the spectrum.

Tables 5 and 6 show the effect of error ΔA_i on unfolding accuracy as a function of ΔT and Q.

Table 5

Weighted-average deviation $\overline{\delta\varphi}$ as a function of the fraction of source neutrons in the total flux, T_{eff} = 0.48 MeV

Energy range ΔE, MeV	Q			
	10%	20%	40%	60%
0.1-15	5.72×10^{-2}	8.62×10^{-2}	1.03×10^{-1}	9.88×10^{-2}

Table 6

Weighted-average deviation $\overline{\delta\varphi}$ as a function of T_{eff} for Q = 60%

Energy range ΔE, MeV	T_{eff}			
	0.48 MeV	0.64 MeV	0.96 MeV	1.12 MeV
0.1-15	9.88×10^{-2}	6.86×10^{-2}	6.70×10^{-2}	9.60×10^{-2}

The weighted-average deviations for an error in A_i of $\pm$ 10% increased by a factor of 1.5-2, and if $\overline{\delta\varphi}$ was within the range 3-7% for exact values of A_i, taking the error into account increased the deviation to 6-10%.

It should be pointed out that introducing an error in the activation integrals did not change the basic tendencies during unfolding, i.e. the greater ΔT, the greater the unfolding error and, likewise, the greater Q, the greater $\overline{\delta\varphi}$.

5. Analysis of results

To explain the above relationships, let us apply the concept of a coefficient for the sensitivity of the activation integral to spectrum temperature. The value of the sensitivity coefficient can be determined from the following expression:

$$\gamma_i = \frac{\partial \ln A_i}{\partial \ln T_{eff}} \qquad (10)$$

and it characterizes the degree of change in the activation integral for a given change of temperature T_{eff}.

Table 7 shows coefficients γ_i as a function of the fraction of source neutrons Q in the total flux for T_{eff} = 0.8 MeV. A strong dependence of γ_i on Q is observed: for certain reactions the sensitivity coefficients change by a factor of 10 or more. This means that when the fraction of source neutrons in the total flux increases, some detectors will stop "reacting" to change in the shape of the secondary neutron spectrum.

This behaviour of γ_i as a function of Q is due to the nature of the energy dependence of threshold reaction cross-sections, which generally have their maximum value at a neutron energy of 14 MeV. Hence, with the exception of the (n,γ)- and several (n,'n)-detectors, the other detectors are activated largely by source neutrons. Clearly, at high values of Q, part of the detectors may have such a small contribution from secondary neutrons to

A_i, that even substantial changes in the shape of the evaporation spectrum cannot noticeably alter the activation integral. This situation is clearly illustrated by the data in Table 7, which shows the contributions of various energy groups of neutrons in a thermonuclear spectrum for Q = 40%. It turned out that not one of the 21 detectors reached more than 1-2% of its total activity in the neutron energy range 5-13 MeV.

The convergence of the unfolded and a priori spectrum at neutron energies of more than 4-5 MeV, which we have already mentioned, comes about

Table 7

Coefficients for the sensitivity of activation detectors to spectrum temperature for various fractions of the 14 MeV source in the spectrum

No.	Detector	Q			
		10%	20%	40%	60%
I	$^{31}P(n,p)$	I,5	I,09	0,59	0,3I
2	$^{32}S(n,p)$	I,44	0,94	0,47	0,23
3	$^{54}Fe(n,p)$	I,44	0,88	0,42	0,2
4	$^{58}Ni(n,p)$	I,39	0,9	0,44	0,2I
5	$^{64}Zn(n,p)$	I,2	0,7	0,3I	0,I5
6	$^{47}Ti(n,p)$	I,05	0,65	0,3	0,I5
7	$^{115}In(n,'n)$	0,96	0,9I	0,79	0,63
8	$^{197}Au(n,\gamma)$	-0,72	-0,72	-0,7I	-0,69
9	$^{115}In(n,\gamma)$	-0,4I	-0,4I	-0,4I	-0,405
IC	$^{63}Cu(n,\gamma)$	-0,5I	-0,49.	-0,44	-0,38
II	$^{103}Rh(n,'n)$	0,54	0,5	0,43	0,33
I2	$^{238}U(n,f)$	0,77	0,54	0,28	0,I5
I3	$^{237}Np(n,f)$	0,29	0,25	0,I6	0,I
I4	$^{27}Al(n,p)$	0,6	0,29	0,II	0,05I
I5	$^{28}Si(n,p)$	0,29	0;I3	0,05	0,02
I3	$^{239}Pu(n,f)$	0,048	0,04	0,028	0,0I8
I7	$^{238}U(n,2n)$	0,I4	0,06	0,023	0,0I
I8	$^{56}Fe(n,p)$	0,II	0,05	0,0I9	0,009
I9	$^{232}Th(n,2n)$	0,09	0,04	0,0I5	0,007
20	$^{24}Mg(n,p)$	0,07	0,03	0,0I2	0,005
2I	$^{27}Al(n,\alpha)$	0,05	0,02	0,009	0,003

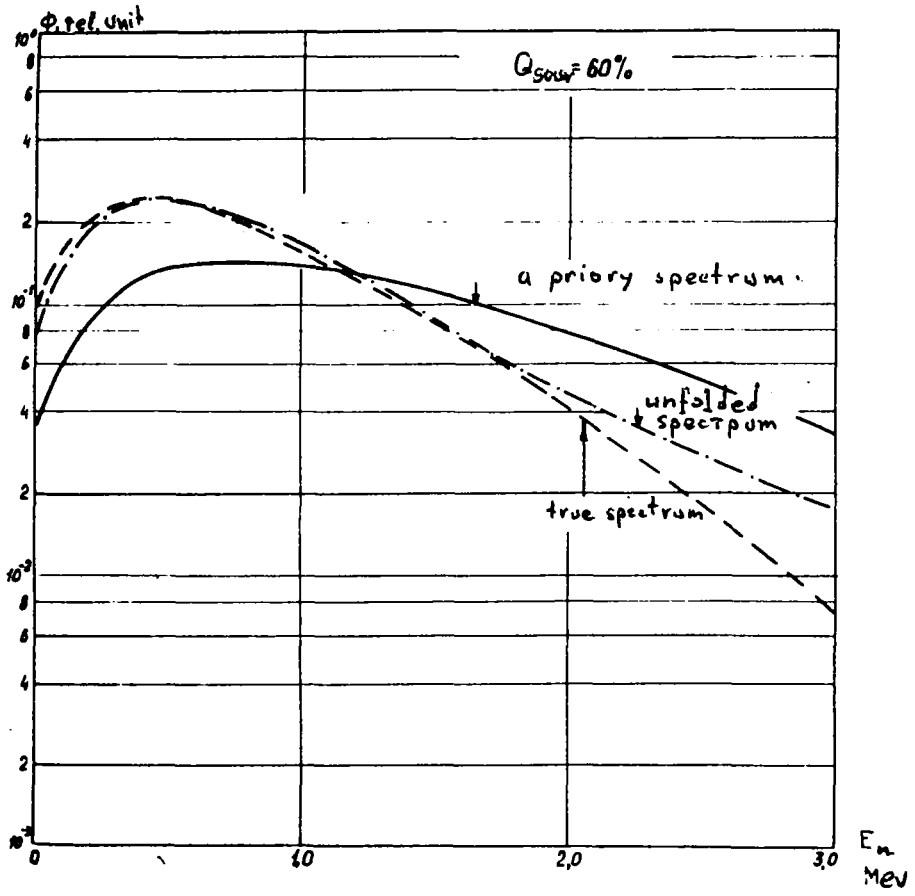

Fig. 6

because this region of the spectrum is very weakly represented in the activation integral. Hence, in unfolding, this part of the neutron spectrum repeats the a priori spectrum virtually without distortion. In addition, the greater the value of Q, the smaller the contribution to the activation integral of neutrons with energies of 5-13 MeV and the smaller the difference between the unfolded and a priori spectra.

Thus, the a priori spectrum is corrected in the unfolding process only over the range in which the detectors attain most of their activity. Accordingly, when unfolding thermonuclear spectra, it will be difficult to ensure acceptable accuracy in the intermediate part of the spectrum. Even when the difference between the desired and the a priori spectrum is insignificant ($\Delta T_{eff} = \pm 20\%$), the difference in the fluxes $\varphi^{unf}(E)$ and $\varphi(E)$ for E = 5-13 MeV may reach 100 or even 1000%. The very stringent requirements that this imposes on the accuracy of the a priori spectrum can hardly be met. At the same time, in the region between 0.1 and 3-4 MeV, even an appreciable

error in the a priori spectrum can be reduced with the help of additional information in the form of activation reaction rates. This is borne out by Fig. 6 which shows the desired (true), a priori and unfolded spectra for Q = 60%.

It should be stressed that these conclusions are based on research using model spectra. A real picture showing the formation of the energy distribution of thermonuclear neutrons would be much more complicated. In particular, so-called direct processes have a probability of occurrence in the interaction of 14 MeV neutrons with most nuclei, and these processes distort the evaporation spectrum of the secondary neutrons. The difference between the evaporation and the real spectrum is particularly noticeable in the energy region 5-10 MeV (neutron fluxes in a thermonuclear spectrum may be several times greater than the corresponding values of the evaporation spectrum). However, the contribution of this neutron group to the total flux being small, the conclusions reached in this work on the whole, remain valid.

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