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Translation of Selected Reports on Neutron Spectrum Unfolding

by Kh. Ya. Bondars, et al

Institute of Physics
Academy of Sciences of the Latvian SSR.
P. Stuchka Latvian State University

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METHODS OF NEUTRON SPECTRUM CALCULATION FROM MEASURED REACTION RATES IN SAIPS. PART I. REVIEW OF MATHEMATICAL METHODS

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INTRODUCTION

Evaluation of neutron spectra from measured reaction rates amounts to solving the equation

$$A_i = \int_0^{E_{max}} \sigma_i(E)\varphi(E)dE \qquad (0.1)$$

with respect to $\phi(E)$, the differential neutron energy density; $\sigma_i(E)$ is the dependence of the neutron cross-section on energy E for the i-th detector, A_i the counting rate of the i-th detector; the integration variable E is neutron energy and E_{max} the upper integration limit. For the given physical application it is sufficient to have E_{max} = 18 MeV.

Equation (0.1) is one of the incorrectly posed problems in mathematics. Various methods are suggested for its solution. Several methods have been developed specially for the given physical application. These methods are not identical with each other because they use different a priori assumptions about the solution sought. Besides, for computer calculations they use neutron cross-section and spectrum libraries of non-identical composition and logical structure, different calculation strategies and so on. Since the equation to be solved is incorrectly posed, these differences can make an appreciable contribution to the solution.

We adapted or used on ES EhVM, operating under the control of OS ES, the currently most common algorithms for calculating neutron spectra from measured reaction rates. These programs, together with the neutron

cross-section and spectrum libraries, are part of the computerized information system SAIPS [2]. The present article describes the basic mathematical concepts used in the algorithms of the SAIPS calculation programs. In the descriptions of the methods the notations used are the same.

1. SAND-II

SAND-II [1, 13, 16] is the most common foreign program. In selecting and analysing the calculation procedure, its authors carried out a large number of test calculations which are contained in the documentation accompanying the program.

First of all, we introduce some notations:

$A_i^{[k]}$ - calculated reaction rate of the i-th detector using the spectrum obtained at the k-th iteration step;

$\phi^{[k]}(E)$ - neutron spectrum obtained at the k-th iteration step;

E_j - energy of the lower boundary of the j-th energy group;

$\Phi_j^{[k]}$ - integral neutron flux in the j-th energy interval between E_j and E_{j+1};

$A_{i,j}^{[k]}$ - part of $A_i^{[k]}$ which lies in the j-th energy interval between E_j and E_{j+1};

$\sigma_r(E)$ - cross-section of the absorber, which can be cadmium, boron, etc;

N_r - number of nuclei of the r-th absorber;

X_r - thickness of the r-th absorber, $barn^{-1}$;

k = 1, 2, ... (iteration index);

i = 1, 2, ... N (detector index);

j = 1, 2, ... M (energy interval index);

r = 1, 2, 3 (absorber index).

X_r is calculated by the formula

$$X_r = \frac{N_0 \rho d 10^{-24}}{A_m},$$

where N_0 is the Avogadro number; ρ the absorber density, cm^3/g; d the absorber thickness, cm; and A_m the absorber atomic weight.

SAND-II uses a 620-group representation of data in the energy range from 10^{-10} to 18 MeV.

In the case of detectors coated with absorbers, we have

$$A_{i,j}^{[k]} = \int_{E_j}^{E_{j+1}} \sigma_i(E)\varphi^{[k]}(E) \prod_{r=1}^{3} e^{-N_r x_r \bar{\sigma}_{r,j}} dE, \qquad (1.1)$$

where $\bar{\sigma}_{r,j}$ is the absorber cross-section $\sigma_r(E)$ averaged over the j-th energy interval. Since SAND-II provides for the use of only three types of absorber (cadmium, boron and gold), the maximum number of absorbers is three.

In SAND-II the absorber cross-sections are averaged on the basis of

$$\bar{\sigma}_{r,j} = \frac{\int_{E_j}^{E_{j+1}} \sigma_r(E)\,dE}{\int_{E_j}^{E_{j+1}} dE}. \qquad (1.2)$$

Thus, the average cross-sections do not depend on "k" and $\phi^{[k]}(E)$. The error due to averaging in this case is insignificant.

In the calculations a detector cross-section averaged over the energy groups is used. The averaging is performed in accordance with the formula

$$\bar{\sigma}_{i,j}^{[k]} = \frac{\int_{E_j}^{E_{j+1}} \sigma_i(E)\varphi^{[k]}(E)\,dE}{\int_{E_j}^{E_{j+1}} \varphi^{[k]}(E)\,dE}. \qquad (1.3)$$

Substituting expression (1.3) into (1.1), we obtain

$$A_{i,j}^{[k]} = \bar{\sigma}_{i,j}^{[k]} \int_{E_j}^{E_{j+1}} \varphi^{[k]}(E) \prod_{r=1}^{3} e^{-N_r x_r \bar{\sigma}_{r,j}} dE. \qquad (1.4)$$

Performing the substitution $\phi^{[k]}(E) = \phi_j^{[k]}$ for $E_j \leq E \leq E_{j+1}$, i.e. going over to group representation, we have

$$\bar{\sigma}_{i,j} = \frac{\int_{E_j}^{E_{j+1}} \sigma_i(E)\,dE}{\int_{E_j}^{E_{j+1}} dE}. \tag{1.5}$$

Since the average cross-section does not depend on "k", $\bar{\sigma}_{i,j}$ can be calculated before carrying out the iterations.

The integral spectrum over the j-th group is determined by the integral

$$\Phi_j^{[k]} = \int_{E_j}^{E_{j+1}} \varphi^{[k]}(E)\,dE. \tag{1.6}$$

Substituting expressions (1.5) and (1.6) into (1.4), we obtain

$$A_{i,j}^{[k]} = \bar{\sigma}_{i,j}\Phi_j^{[k]} \prod_{r=1}^{3} e^{-N_r X_r \bar{\sigma}_{r,j}} \tag{1.7}$$

and

$$A_i^{[k]} = \sum_{j=1}^{M} A_{i,j}^{[k]}. \tag{1.8}$$

We introduce the notations

$$\begin{cases} W_{i,j}^{[k]} \equiv \dfrac{1}{2}(A_{i,j}^{[k]} + A_{i,j-1}^{[k]})/A_i^{[k]} \text{ for } \quad j = 2, \ldots, M, \\ W_{i,M+1} \equiv A_{i,M+1}^{[k]}/A_i^{[k]}, \\ W_{i,1}^{[k]} \equiv A_{i,1}^{[k]}/A_i^{[k]}. \end{cases} \tag{1.9}$$

If

$$\sum_{i=1}^{N} W_{i,j}^{[k]} \neq 0, \tag{1.10}$$

the neutron spectrum is determined by the formula

$$\varphi_j^{[k+1]} = \varphi_j^{[k]} \exp\{C_j^{[k]}\}, \tag{1.11}$$

where

$$C_j^{[k]} = \sum_{i=1}^{N} W_{i,j}^{[k]} \ln\left(\frac{A_i}{A_i^{[k]}}\right) \Big/ \sum_{i=1}^{N} W_{i,j}^{[k]}. \tag{1.12}$$

Subsequently, the concept of smoothness was introduced, which means that the definition of $W_{i,j}^{[k]}$ is modified [1, 13, 17]:

$$W_{i,j}^{[k]} = \sum_{i=l_1}^{l_2} A_{i,j}^{[k]} / [(l_2 - l_1 + 1) A_i^{[k]}], \quad j = 2, 3, \ldots, M-1, \tag{1.13}$$

where

$$l_1 = \begin{cases} 1 \text{ for } j = 2, 3, \ldots, \dfrac{N_s - 1}{2}; \\ j - \left(\dfrac{N_s - 1}{2}\right) \text{ for } j = \left(\dfrac{N_s + 1}{2}\right), \ldots, \left(M - \dfrac{N_s - 1}{2}\right), \\ 2j - M \text{ for } j = \left(M - \dfrac{N_s - 3}{2}\right), \ldots, (M-1); \end{cases} \tag{1.14}$$

$$l_2 = \begin{cases} 2j - 1 \text{ for } j = 2, 3, \ldots, \left(\dfrac{N_s - 1}{2}\right), \\ j + \left(\dfrac{N_s - 1}{2}\right) \text{ for } j = \left(\dfrac{N_s + 1}{2}\right), \ldots, \left(M - \dfrac{N_s - 1}{2}\right); \\ M \text{ for } j = \left(M - \dfrac{N_s - 3}{2}\right), \ldots, (M-1); \end{cases} \tag{1.15}$$

$$W_{i,M}^{[k]} = (5A_{i,M}^{[k]} + 2A_{i,M-1}^{[k]} - A_{i,M-2})/6A_i^{[k]}, \tag{1.16}$$

$$W_{i,1}^{[k]} = (5A_{i,1}^{[k]} + 2A_{i,2}^{[k]} - A_{i,3}^{[k]})/6A_i^{[k]}. \tag{1.17}$$

N_s is the smoothing parameter defining the number of points over which smoothing is performed.

It was necessary to introduce the concept of smoothing because physically unjustified oscillations appear in the energy regions where certain detectors like resonance detectors, for example, operate. In test calculations the SAND-II authors chose the smoothing procedure outlined above. The greatest number of points over which smoothing is performed in SAND-II is $N_s = 75$.

Interpolation or extrapolation is carried out for the j for which the inequality in expression (1.10) is not satisfied. The formula

$$\varphi(E)=aE^{b} \tag{1.18}$$

is used for interpolation between the nearest j for which expression (1.10) does not hold. The unknown coefficients a and b are determined from the matching condition. If extrapolation has to be carried out, then on the low-energy side one can choose, depending on the need, extrapolation functions ~1/E; $\sim\sqrt{E}$ or a Maxwellian thermal neutron spectrum for a given temperature. On the side of high energies the extrapolation can be performed using the fission or fusion neutron spectrum function.

The iterative process stops when one of three conditions is fulfilled:

(1) The specified number of iterations has been attained;

(2) The value of

$$\varepsilon=\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{A_i-A_i^{[k]}}{A_i^{[k]}}\right)^2}{N-1}} \tag{1.19}$$

becomes smaller than a pre-specified value which should be related to the measurement error;

(3) If ε varies by not more than 1% between two successive iterations.

After completion of the iterative process we verify by what factor the largest discrepancy between a measured reaction rate and the corresponding calculated reaction rate differs from ε. If this number is greater than the pre-specified number, the iterative process starts afresh after rejection of this reaction rate.

2. DIRECTED DIFFERENCE METHOD

This method has been developed on the basis of Refs [7, 10], in which a statistical representation of the integral equation in expression (0.1) and a number of transformations for finding the solution are used to determine the functional

$$S(\varphi(E))=\frac{1}{N}\sum_{i=1}^{N}\ln\frac{1}{\int_0^{E_{max}}\frac{\sigma_i(E)}{A_i}\varphi(E)\,dE}. \qquad (2.1)$$

It is pointed out in Ref. [7] that the minimum of a functional of this type can be obtained by using the iteration relationship

$$\varphi^{[k+1]}(E)=\varphi(E)^{[k]}\frac{\sum_{i=1}^{N}\sigma_i(E)/A_i^{[k]}}{\sum_{i=1}^{N}\sigma_i(E)/A_i}. \qquad (2.2)$$

Several different computer programs have been developed for calculating neutron spectra with formula (2.2): MINSK-22 [5], MINSK-32 [4], NAIRI [7] and so on. These programs use different calculation strategies.

Formulae (1.11) and (2.2) are similar near the solution. To show this, near the solution we write

$$A_i^{[k]}=A_i+\Delta_i^{[k]}, \qquad (2.3)$$

where $\Delta_i^{[k]}/A_i$ is a quantity of the first order of smallness. Retaining only terms of the first order of smallness, we can then write

$$\ln\frac{A_i}{A_i^{[k]}}=\ln\frac{A_i}{A_i+\Delta_i^{[k]}}\approx-\frac{\Delta_i^{[k]}}{A_i}. \qquad (2.4)$$

Taking expression (2.4) into account in Eq. (1.11), we have

$$\varphi_j^{[k+1]}=\varphi_j^{[k]}\exp\frac{\sum_{i=1}^{N}W_{i,j}^{[k]}\left(-\frac{\Delta_i^{[k]}}{A_i}\right)}{\sum_i W_{i,j}^{[k]}}. \qquad (2.5)$$

Expanding the exponent into a series and retaining only terms of the first order, we obtain

$$\varphi_j^{[k+1]} \approx \varphi_j^{[k]} \left(1 - \frac{\sum_{i=1}^{N} W_{i,j}^{[k]} \frac{\Delta_i^{[k]}}{A_i}}{\sum_{i=1}^{N} W_{i,j}^{[k]}} \right) \tag{2.6}$$

Taking expression (1.9) into account and substituting

$$A_{i,j}^{[k]} = \bar{\sigma}_{i,j} \Phi_j^{[k]}, \tag{2.7}$$

we obtain

$$\varphi_j^{[k+1]} \approx \varphi_j^{[k]} \frac{\sum_{i=1}^{N} \frac{\bar{\sigma}_{i,j}}{A_i^{[k]}}}{\sum_{i=1}^{N} \frac{\bar{\sigma}_{i,j}}{A_i}}. \tag{2.8}$$

As will be seen, the difference between expressions (2.8) and (2.2) lies only in the manner of representing the cross-sections and spectra.

Considering the similarity between expressions (2.8) and (1.11) from the program standpoint, a variant of SAND-II has been developed using the iteration formula of the directed difference method.

3. SPECTRA, RFSP JÜL AND GIN

The algorithm used in these programs is described in Ref. [14] and applied in the SPECTRA program. L. Turi and A. Fischer somewhat modified the calculation method and developed RFSP [11]. At present the latest version, RFSP JÜL [20], is best known. The algorithm of the GIN program was developed by K.I. Zolotarev [6] on the basis of the RFSP algorithm.

In this procedure it is assumed that

$$E\varphi(E)=\sum_{j=1}^{M} d_j W_j(E), \tag{3.1}$$

holds for the function sought, where d_j represents the coefficients dependent on the set of functions $W_j(E)$, and that for the spectrum sought

$$W_j(E)=\frac{E-E_{j-1}}{E_j-E_{j-1}} H_j(E)\,(1-\delta_{j,1})+\frac{E_{j+1}-E}{E_{j+1}-E_j} H_{j+1}(E)\,(1-\delta_{j,m}), \tag{3.2}$$

where

$$\begin{cases} H_j(E)= \begin{cases} 1, \text{ if } & E_{j-1}\leqslant E\leqslant E_j, \\ 0, \text{ if } & E<E_{j-1} \text{ и } E>E_j, \end{cases} \\ \delta_{i,l}- \text{ Kroenecker symbol:} \\ \qquad \delta_{i,l}= \begin{cases} 1 & i=l, \\ 0 & i\neq l. \end{cases} \end{cases} \tag{3.3}$$

Taking expression (3.2) into account, we have

$$d_j=E_j\varphi(E_j). \tag{3.4}$$

Making these assumptions, we can write the activation equation in the form

$$A_i=\sum_{j=1}^{M} Q_{i,j}\varphi(E_j), \tag{3.5}$$

where

$$Q_{i,j}=E_j\int_{E_j}^{E_{j+1}}\frac{\sigma_i(E)}{E}\left[\frac{E-E_{j-1}}{E_j-E_{j-1}}(1-\delta_{j,1})+\frac{E_{j+1}-E}{E_{j+1}-E_j}(1-\delta_{j,M})\right]dE. \tag{3.6}$$

To solve Eq. (3.5) we construct the functional

$$\Delta=\sum_{i=1}^{N}\left(A_i-\sum_{j=1}^{M} Q_{i,j}\varphi(E_j)\right)^2 F_i^2+\sum_{j=1}^{M}(\varphi(E_j)-\varphi_0(E_j))^2 G_j^2, \tag{3.7}$$

where $\phi_0(E)$ is an a priori function and F_j^2 and G_j^2 are arbitrary coefficients which, according to Fischer and Turi [11], should be

$$\frac{1}{A_i^2} \text{ и } \left(\frac{1}{\varphi(E)}\right)^2.$$

Differentiating Eq. (3.7) with respect to $\phi(E_h)$ (h = 1, 2, ..., M) and setting the result equal to zero, we obtain a system of equations for finding $\phi(E_j)$:

$$\sum_{i=1}^{N}\left(A_i-\sum_{j=1}^{M}Q_{i,j}\varphi(E_j)\right)Q_{i,h}F_i^2+\sum_{j=1}^{M}(\varphi(E_j)-\varphi_0(E_j))\,G_j^2=0 \quad (3.8)$$

or, after simple transformations, we have

$$\sum_{i=1}^{N}A_iQ_{i,h}F_i^2-\sum_{j=1}^{M}\varphi_0(E_j)\,G_j^2=\sum_{j=1}^{M}\left(\sum_{i=1}^{N}Q_{i,j}Q_{i,h}F_i^2-G_j^2\right)\varphi(E_j). \quad (3.9)$$

The solution procedure amounts to determining $\phi(E_j)$ from the system of equations in expression (3.9) and using the solution obtained as a first approximation in the next iteration step. To stop the iteration, we specify the maximum number of iterations or indicate the value of the equation

$$\varepsilon=\frac{1}{N}\sum_{i=1}^{N}\left|\frac{A_i-A_i^{[k]}}{A_i}\right|, \quad (3.10)$$

at which the iteration process is to stop.

The main difference between SPECTRA on the one hand and RFSP and GIN is that an expansion of $\phi(E)$, not $E_\phi(E)$, is used in Eq. (3.1).

4. CRYSTAL BALL AND WINDOWS

The algorithm of these programs is based on considerations set out in Ref. [18]. We describe the method following Ref. [15], which deals with its use for a specific physical application. The method has been developed further in WINDOWS [19].

It is assumed that A_i has been measured with an error and is related to the true spectrum $\phi(E)$ by the relation

$$A_i=\int_0^\infty\varphi(E)\sigma_i(E)dE+\varepsilon_i, \quad (4.1)$$

where ε_i is the measurement error evaluated as

$$\nu_i^2 = \left(\frac{\overline{e_i}}{A_i}\right)^2, \tag{4.2}$$

and that we know the function $\psi(E)$ which does not differ much from the function sought. We define the solution as a function which simultaneously minimizes

$$S^2 = \int_0^\infty \left[\frac{d}{dE}\left(\frac{\varphi(E)}{\psi(E)}\right)\right]^2 W(E)\,dE \tag{4.3}$$

and

$$f = \sum_i \left(\frac{e_i}{\nu}\right)^2, \tag{4.4}$$

where W(E) is a weighting function recommended by Kam and Stallmann [15] for use in the given physical application, ~1/E. We introduce some notations:

$$S_i \equiv \int_0^\infty \sigma_i(E)\psi(E)\,dE; \tag{4.5}$$

$$S_i(E) \equiv \frac{1}{S_i}\int_0^E \sigma_i(E)\psi(E)\,dE; \tag{4.6}$$

$$K^*_i(E) \equiv S_{i+1}(E) - S_i(E); \tag{4.7}$$

$$\beta_i \equiv \frac{A_{i+1}}{S_{i+1}} - \frac{A_i}{S_i}. \tag{4.8}$$

Integrating by parts, instead of expression (4.8) we obtain

$$\beta_i = -\int_0^\infty K^*(E)\frac{d}{dE}\left(\frac{\varphi(E)}{\psi(E)}\right)dE + \frac{e_{i+1}}{S_{i+1}} - \frac{e_i}{S_i}. \tag{4.9}$$

Instead of the function sought, we use the series

$$\bar{\Phi}_j = \psi(E_j)\left[\frac{A_{i_0(j)}}{S_{i_0(j)}} + \sum_{i=1}^{N-1} C_{i,j}\beta_i\right]. \tag{4.10}$$

The subscript $i_0(j)$ may be chosen arbitrarily; let us note only that $A_{i_0}(j)$, which gives more information at energy E_j, leads to better results.

Let me introduce the notations

$$D_j(E) = \begin{cases} 0 \text{ for } E < E_j, \\ 1 \text{ for } E \geqslant E_j. \end{cases} \tag{4.11}$$

$$D^*_j(E) = D_j(E) - S_{i_0(j)}(E). \tag{4.12}$$

We then construct the difference

$$\frac{\varphi(E_j) - \bar{\Phi}_j}{\psi(E_j)} = \int_0^\infty \left(D^*_j(E)\, d + \sum_i C_{i,j} K^*_i(E) \frac{d}{dE}\left[\frac{\varphi(E)}{\psi(E)}\right]\right) dE + \\ + \frac{\varepsilon_{i_0(j)}}{S_{i_0(j)}} - \sum_i C_{i,j}\left(\frac{\varepsilon_{i+1}}{S_{i+1}} - \frac{\varepsilon_i}{S_i}\right). \tag{4.13}$$

This is a linear functional of $\frac{d}{dE}\left[\frac{\varphi(E)}{\psi(E)}\right]$ and ε_1. Minimization of the norm of this functional in Hilbert space is equivalent to the minimization of

$$S^2 + \gamma^2 f, \tag{4.14}$$

where γ^2 defines the relation between the degree of approximation and the error. Proceeding from the minimization conditions, we arrive at a system of equations for determining $C_{i,j}$:

$$\sum_{i=1}^{N-1} C_{i,j}\left[\int_0^\infty K^*_i(E) K^*_k(E) W^7(E)\, dE + (\gamma_i + \gamma_{i+1})\delta_{i,k} - \gamma_i \delta_{i,k+1} - \gamma_{i+1}\delta_{i+1,k}\right] = \\ = \int_0^\infty D^*_j(E) K^*_k(E) W^7(E)\, dE - \gamma_{i_0(j)}\delta_{i_0(j),k+1} + \gamma_{i_0(j)}\delta_{i_0(j),k}, \tag{4.15}$$

where $\gamma_i = \gamma_0 \left(\frac{A_i}{S_i}\frac{1}{p_i}\right)^2$,

γ_0 is an arbitrary constant;

$\frac{1}{p_i}$ defines the relative error of A_i, i.e. $\nu_i = A_i \frac{1}{p_i}$; $k = 1, \ldots, n-1$;

and $\delta_{i,k}$ is the Kroenecker symbol:

$$\delta_{i,k} = \begin{cases} 1 & i = k, \\ 0 & i \neq k. \end{cases}$$

The calculation starts from γ_0, which gives a positive solution over the entire energy range. The result obtained is used as the next first approximation, and in calculating the next approximation the coefficient γ_0 is reduced at the same time, whereby a better convergence is obtained in the measured and the calculated integral. The process is continued until the pre-specified error ε_1 is attained. There is provision for indicating the maximum number of iterations.

5. ALGORITHM OF THE POLYNOMIAL METHOD

The polynomial method can be described as one of the RDMM methods [7]. SAIPS includes the polynomial method, which is based on an earlier program written in ALGOL-60 for the TA-1M translator [3]. The new variant of the program is written in the PL/1 language. The program uses the SAND format of cross-section and spectrum representation.

It is assumed that the neutron spectrum can be represented in the form

$$\varphi(E) = W(E)D(E), \tag{5.1}$$

where W(E) is a weighting function chosen on the basis of physical considerations and D(E) is a "deformation" function which we seek in the form of a power series with unknown coefficients b_k:

$$D(E) = \sum_{k=1}^{K} b_k E^{k-1}. \tag{5.2}$$

Substituting expression (5.2) into the activation equation, we obtain

$$A_i = \sum_{k=1}^{K} b_k \int_0^{E_{max}} W(E)E^{k-1}\sigma_i(E)dE. \tag{5.3}$$

Let us introduce the notations

$$J_{i,k} = \int_0^{E_{max}} W(E)E^{k-1}\sigma_i(E)dE. \tag{5.4}$$

Then, instead of expression (5.3), we can write

$$A_i = \sum_{k=1}^{K} b_k J_{i,k}. \tag{5.5}$$

$J_{i,k}$ depends on the experimental values and A_i is measured directly in the experiment. In such a case, the method of least squares is the "natural method" of evaluation. In our case, it amounts to determining b_k from the condition that the quantity

$$\varepsilon_k^2 = \sum_{i=1}^{N} \left(A_i - \sum_{k=1}^{K} b_k J_{i,k} \right)^2 p_i, \tag{5.6}$$

must be minimum. Here p_i is the weight of the i-th term in the sum and K must be smaller than N.

In the usual manner we arrive at a system of normal equations from which we find b_k [8, 9]:

$$\begin{cases} b_1[Z^{(1,1)}p] + b_2[Z^{(1,2)}p] + \cdots + b_K[Z^{(1,K)}p] = [AZ^{(1)}p], \\ b_1[Z^{(2,1)}p] + b_2[Z^{(2,2)}p] + \cdots + b_K[Z^{(2,K)}p] = [AZ^{(2)}p], \\ \text{---------------------------} \\ \text{---------------------------} \\ b_1[Z^{(K,1)}p] + b_2[Z^{(K,2)}p] + \cdots + b_K[Z^{(K,K)}p] = [AZ^{(K)}p], \end{cases} \tag{5.7}$$

where the following notations have been introduced:

$$\begin{cases} Z_i^{(k)} = \int_0^{E_{max}} W(E)\sigma_i(E)E^{k-1}dE, \\ Z_i^{(h,k)} = Z_i^{(h)}Z_i^{(k)} \end{cases} \tag{5.8}$$

and the Gauss summation symbols are used:

$$\begin{cases} [Z^{(h,k)}p] = \sum_i Z_i^{(h,k)}p_i, \\ [AZ^{(k)}p] = \sum_i A_i Z_i^k p_i. \end{cases} \tag{5.9}$$

Along with the system in expression (5.7), the following system is solved with respect to Q for k = 1, ..., K:

$$\begin{cases} Q_{k,1}[Z^{(1,1)}p] + Q_{k,2}[Z^{(1,2)}p] + \cdots + Q_{k,K}[Z^{(1,k)}p] = \delta_{k,1}, \\ Q_{k,1}[Z^{(2,1)}p] + Q_{k,2}[Z^{(2,2)}p] + \cdots + Q_{k,K}[Z^{(2,K)}p] = \delta_{k,2}, \\ \text{---------------------------} \\ \text{---------------------------} \\ Q_{k,1}[Z^{(K,1)}p] + Q_{k,2}[Z^{(K,2)}p] + \cdots + Q_{k,K}[Z^{(K,K)}p] = \delta_{k,K}, \end{cases} \tag{5.10}$$

where δ is the Kroenecker symbol defined by the equality

$$\delta_{k,r} = \begin{cases} 1 \text{ for } k=r, \\ 0 \text{ for } k\neq r. \end{cases}$$

The roots of the system in expression (5.10) are the elements of a correlation matrix:

$$\begin{Vmatrix} Q_{1,1} & Q_{1,2} - - - - - - - & Q_{1,K} \\ Q_{2,1} & Q_{2,2} - - - - - - - & Q_{2,K} \\ - - - - - - - - - - - - - \\ - - - - - - - - - - - - - \\ Q_{1,K} & Q_{2,K} \quad - - - - - - & Q_{K,K} \end{Vmatrix} \qquad (5.11)$$

The root-mean-square error of the neutron spectrum is determined by the formula

$$\Delta\varphi = \mu_\varphi \sqrt{\frac{1}{p_\varphi}}, \qquad (5.12)$$

where

$$\mu_\varphi = \sqrt{\frac{\varepsilon^2}{(N-K)}} \qquad (5.13)$$

is the root-mean-square error of the weight. The reciprocal weight $1/p_\phi$ is calculated by the formula

$$1/p_\varphi = \sum_{k,\,n=1} \varphi_k \varphi_n Q_{k,n}, \text{ where } \varphi_k = \left(\frac{\partial \varphi}{\partial b_k}\right). \qquad (5.14)$$

The systems of linear equations are solved by the iterative method using double precision [12].

It has been established that physically satisfactory solutions are obtained at the minimum of ε_K^2 as a function of K.

The advantage of this method lies in the fact that it is possible to give an evaluation of the errors.

CONCLUSION

The review describes the principal methods which are finding wide use in various laboratories of the world. The methods included in the SAIPS computerized information system have been verified repeatedly in test examples of "paper" and actual experiments. In the case of the latter, the results were compared with independent spectrum evaluations - direct measurements, calculations by the Monte Carlo method and other theoretical calculations. Comparisons of the methods and programs for neutron spectrum unfolding from measured reaction rates are being conducted at the international and All-Union levels. It should, however, be borne in mind that neutron spectrum evaluation cannot be separated from the physical conditions under which it is performed, i.e. spectrum evaluation must not be reduced to the trivial application of a particular method of neutron spectrum unfolding. It is necessary beforehand to familiarize oneself with spectrum evaluation results obtained under similar conditions and with the characteristics of the detectors used under specific conditions, to perform theoretical calculations and to study the recommendations on the use of particular dosimetric files of detector cross-sections.

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Methods of neutron spectrum calculation from measured reaction velocities* in SAIPS.

Part 2. Software and data input

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At the All-Union School on "Metrology of Neutron Measurements in Nuclear Physics Facilities", held at Riga in 1976, the need was felt for a library of programs for neutron spectrum calculations from measured reaction velocities, and it was decided to establish such a library. The neutron spectra are unfolded by non-identical mathematical techniques applied in the form of different programs and several neutron cross-section libraries. When a user (physicist) needs to perform calculations, he faces a number of problems: obtaining or generating calculation programs, comparing these programs, generating a library of reference spectra, study of calculated spectra and so on. This means routine work which is duplicated in many laboratories. To help solve these problems a computerized information system called SAIPS has been developed, some aspects of which are dealt with in Refs [1-4]. The present paper gives a short description of data input into SAIPS and the basic principles of its utilization.

SAIPS is based on the ES 1022 computer controlled by the operational system OS ES version 4.1. It contains the programs needed for unfolding spectra, neutron cross-section and reference spectrum libraries and the software for the main system and for computerized calculations.

1. The following programs have been fed in, adapted and checked, and are recommended for calculations in SAIPS: SAND II [11, 22], WINDOWS [24], RFSP-JUL [14] and RM [5]. In addition, SAIPS has several other programs (see Table 1), which can be used in calculations although these duplicate the above-mentioned programs and are more restricted. They include: CRYSTAL BALL [19], in which the solution method is borrowed from WINDOWS; SPECTRA [15, 16], RFSP [9] and GIN [6] using the same solution algorithm which is used in the most advanced form of RFSP-JUL; and LIKMET, which uses the maximum likelihood method [8]. Table 2 gives the data on the computer

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* Read: "reaction rates"

resources used by the different calculation programs. The calculation time was determined by calculating a variant with 11 detectors. The criterion for ending the calculation in all programs was so chosen that the calculated activation integrals did not differ from the reference ones by more than 5%. The real time is the time of calculation in a single-program operation. The commercial time is the "count" of the computer resources used by the calculation programs: processor employment time, volume of operational memory, intensity of use of external devices and so on. All calculation programs, except RM, are written in FORTRAN IV. Therefore, the operational memory volume occupied by the calculation programs depends on the maximum planned size of arrays. This deficiency was removed by using the PL/1 language to write the RM program. Because of the high degree of compatibility of the third-generation computers (ES EhVM and IBM) at both the hardware and software levels the spectrum unfolding programs could be adapted and used in the calculations without changes. In addition, modified versions with changes in data output have been designed. The results obtained are first recorded in an intermediate data set, from where they are printed out in the desired form.

At present, the following cross-section libraries have been adapted in SAIPS: ENDF/B-IV [21]; ENDF/B-V [20]; dosimetric file ZACRSS [4]; BOSPOR 78 [7]; libraries coming with the calculation programs: SAND II (a library known as CCCII2B and in the modified version DETAN 74 [23]; WINDOWS, RFSP-JUL and some individual cross-sections. SAIPS altogether contains cross-sections for more than 60 reactions used in spectrum unfolding. During calculations the spectrum libraries of the SAND II program from Refs [5] and [18] can be used as a first approximation.

2. In using SAIPs for calculations the physicist has no need to go into programming problems. In order to achieve this purpose, we propose that the operation of SAIPS should be divided into three levels, each supported by its own software.

Level 1 includes: adaptation, generation and checking of calculation programs and cross-section and spectrum libraries; generation of software for computerized calculations, use of cross-section and spectrum libraries, updating and further development of the system; dissemination of the distributive variant of the system and so on. These operations are centralized so that duplication of work in many laboratories is avoided and the physicist is freed from routine work. Operations at this level are carried out by programmers with the help of physicists.

Level 2 is related to the operation of SAIPS with specific hardware and software. The main program of SAIPS occupies up to 150 kb of operational memory. The distributive variant contains: program loading modules, neutron spectrum libraries and a library of catalogued procedures. Operations at the second level are performed by the computer personnel using the standard tools of the operational system.

Level 3 is where calculations are performed. The user obtains access to the system by means of the user language and the specific operational system of OS ES. The set of SAIPS catalogued procedures facilitates access to the system. The user language is based on the terminology used in the present paper, so the user has no need to learn it. SAIPS provides the following facilities:

- Unified generation of input of initial data and output of results for different calculation methods;
- Reduction in the number of input parameters;
- Changes of cross-section libraries and individual cross-sections;
- Consideration of the presence of one or more absorbers which can cover detectors;
- Feeding of an a priori spectrum from the input flow or selection from a specified library or selection from a specified library in the sense of least squares, whichever is most suitable.

3. SAIPS provides the opportunity to determine the reliability of the unfolded neutron spectrum and to plan measurement and calculation programs by varying a number of factors: errors in reaction velocities; errors in the cross-sections used; detector array; a priori information, spectrum unfolding programs and so on. The information content and the possibilities offered by the system enable such calculations to be made without much effort on the part of the user. It should be noted however that when a problem is incorrectly posed great care must be taken in generalizing the results of such studies. A priori information on the spectrum must be provided after studying the physical conditions determining the shaping of the neutron spectrum to be unfolded. Usually such a priori information is a first approximation in the spectrum unfolding programs. The influence of the above-mentioned factors is studied at the stage of planning on the basis of the a priori neutron spectrum. The detector array, the accuracy of the reaction velocity measurements, the

permissible uncertainty in the a priori information, etc. are determined as a function of the requirements applicable to the neutron spectrum to be unfolded. After unfolding, such calculations are performed in order to determine the error in the neutron spectrum obtained. Specific operations in each case depend on the unfolding requirements, the preceding experiment and so on. The method described involves the expenditure of considerable computer resources but, if we bear in mind that the problem to be handled is incorrectly posed, it is often not possible to do without such calculations.

CONCLUSIONS

A large set of libraries of cross-sections, spectra and so on in practice represents a "data cemetery". In spite of the availability of information, the user may not be aware of its existence; he has to make an independent assessment of its value, generate the tools of utilization and so on. The development of systems like SAIPS qualitatively changes the user-data relationship since it not only provides information but also the tools for its utilization.

The further development of SAIPS will involve the unification of a wider range of programs and initial data for neutron spectrum calculations. For this purpose, we are adapting the cross-sections of the full ENDF/B-IV file obtained from the IAEA, the treatment program for the AMPX II cross-section libraries [17] and the ANISIN [13] and MORSE [12] calculation programs obtained from the Radiation Shielding Information Center (RSIC), Oak Ridge, USA.

Table 1. SAIPS Spectrum unfolding programs

Program	Unfolding method	Computer on which program used	Number of energy groups or points	Maximum number of detectors	Source	Remarks
1. SAND II	SAND II	IBM/360 ES EhVM CDC 6600	620	35	RSIC	
2. MMPS	MMP and SAND II	ES EhVM	620	35		Modified SAND II
3. CRYSTAL BALL	CRYSTAL BALL	IBM/360 ES EhVM	621	20 or 40	RSIC	
4. WINDOWS	CRYSTAL BALL	IBM/360 ES EhVM	621	15 or 40	RSIC	CRYSTAL BALL method improved and further developed
5. SPECTRA	SPECTRA	CDC 6600 ES EhVM	up to 100	30	RSIC	Adapted program translated into PL/1 for ES EhVM
6. RFSP	SPECTRA	ICT-1905	up to 50	30	Author	Based on SPECTRA
7. RFSP JUL	SPECTRA	IBM/360 ES EhVM	up to 100	30	RSIC	Based on RFSP and SPECTRA
8. GIN	SPECTRA	ES EhVM	100	30	Author	Based on RFSP and SPECTRA
9. RM	Polynomial method	ES EhVM	Specified by user	Specified by user	Ours	Program written in PL/1 permitting dynamic use of memory
10. OBR 30	Statistical regularization /10/	BEhSM-6 ES EhVM	50	20	Author	Modification of program generated for neutron spectrum unfolding at Moscow Engineering Physics Institute (MIFI)

Table 2. Computer resources used by the calculation programs

No.	Program	Calculation time, min		Operational memory occupied, kilobyte
		Real	Commercial	
1.	SAND II	2.5	6.5	112
2.	RM	1.7	4.5	136
3.	RFSP JUL	12.7	21	234
4.	WINDOWS	2	5	248

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PHYSICS OF THE ATOMIC NUCLEUS AND ATOMIC AND MOLECULAR SPECTROSCOPY

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USING THE SAND-II AND MLM METHODS TO RECONSTRUCT FAST NEUTRON SPECTRA

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The reconstruction of fast neutron spectra from measured reaction rates may be reduced to the solution of Fredholm's integral equation of the first kind:

$$A_i = \int_0^{E_{max}} \sigma_i(E)\varphi(E)dE \quad (i=1,2,\dots M), \qquad (1)$$

where: A_i is the measured reaction rate of the i-th detector;

$\sigma_i(E)$ is the given energy dependence of the i-th reaction's cross-section;

$\varphi(E)$ is the differential energy dependence of the neutron flux density (unknown function); and

M is the number of detectors.

For a large range of problems it is sufficient to set the upper integration limit E_{max} at $\sim$ 18 MeV.

This problem falls in the category of incorrectly formulated problems, and so additional information is required concerning the unknown function [7], i.e. concerning the differential energy dependence of the neutron flux density $\varphi(E)$.

There are various methods for seeking a solution to the problem as formulated above. One of the best-known methods used in the USSR is the maximum likelihood method (MLM) [5] (or directional difference method (DDM)), whereas SAND-II is commonly used abroad [9, 10] .

The purpose of this paper is to compare the MLM [6] and SAND-II [10] methods, taking as an example the processing of measurement data which were obtained in the B-2 beam line at the BR-10 reactor in order to determine the composition of shielding for a fast reactor [4, 8].

In reconstructing the fast neutron spectra we used LIKMET, one of the programs developed for the MLM at the Moscow Institute of Physical Engineering, for use on the ES and BEhSM-6 computers. The LIKMET program can be used with the cross-section from the SAIPS data processing system [1, 2].

Table 1 gives the reaction rates for detectors placed behind steel-graphite shielding of thickness Z = 6.5 cm and Z = 42.5 cm. The energy range of the detectors is also shown (corresponding to a 90% contribution to the reaction rate after a 5% deduction has been made in the low-energy and high-energy parts of the spectrum). Since the spectrum is distorted in a physically unjustifiable way if the cross-section for the $^{35}Cl(n,\alpha)^{32}P$ reaction recommended in Ref. [3] is used, we selected the cross-section for this reaction on the basis of the recommendations made in Ref. [6].

The spectra were reconstructed by means of both methods with a unified energy grouping (620 groups for SAND-II). The efficiency of both methods was checked against a test problem in which the right-hand side corresponded to the reaction rates obtaining with the Watt fission spectrum:

$$\varphi_0(E) = 0{,}484 \exp(-E) \operatorname{sh} \sqrt{2E}. \qquad (2)$$

Tables 2 and 3 give the results of neutron spectrum reconstruction [4] by the MLM and SAND-II methods for shielding thicknesses of Z = 6.5 cm and Z = 42.5 cm, respectively. The spectra were reconstructed on the basis of three initial approximations. For the first type of approximation, the spectrum was reconstructed by the SAND-II program with detector cross-sections taken from the ZACRSS library [1]; as an initial approximation we took the spectrum from the SAIPS standard spectrum library which gives the best fit with the measured reaction rates. The BGS-1 library was used for spectrum reconstruction by means of the LIKMET program. In both cases the $^{35}Cl(n,\alpha)^{32}P$ reaction cross-section was taken from Ref. [6] and the $^{31}P(n,p)^{31}Si$ cross-section from the SAND-II library. With the MLM method, the reference spectrum was expressed as $\varphi_o(E) = \exp(-\mu E)$, where μ is a factor determined by analysing the high-energy part of the integral spectrum. For the other two types of approximation, the same reference spectra were used, i.e. the 1/E spectrum and the Watt fission neutron spectrum. Apart from the $^{35}Cl(n,\alpha)^{32}P$ and $^{31}P(n,p)^{31}Si$ reactions, the cross-sections were taken from the ZACRSS library.

The following conclusions may be drawn from the results:

(1) Both methods give similar values for the differential spectrum (< 10% difference) using the same cross-section libraries and standard spectra;

(2) For the given set of detectors, the values in the differential neutron spectrum in the 0.5-1.5 MeV region are 15-30% lower with the BGS-1 data than with the ZACRSS data. This is due to the different $^{103}Rh(n,n')^{103}Rh^m$ and $^{115}In(n,n')^{115}In^m$ reaction cross-section data in the ZACRSS and BGS-1 libraries;

(3) If the initial neutron spectrum is incorrectly selected, the resulting spectrum may be considerably distorted, especially in energy regions where experimental data are scarce. This emerges clearly from the results of spectrum reconstruction (Tables 2 and 3) in the 5.5-12 MeV region, if the 1/E spectrum is used as an initial approximation.

The selection of cut-off criteria in the solution refinement sub-routines also has an important influence. If they are taken significantly too high or too low, further distortion of the spectrum results. In the

case in question, an integral criterion was selected for both methods, the cut-off being introduced when the resulting spectrum made a given match with the measured detector count rates.

Tables 4 and 5 show the integral energy dependences of fast neutron flux densities with $E_n \geqslant 3.0$ MeV, $E_n \geqslant 2.6$ MeV, $E_n \geqslant 1.0$ MeV, and $E \geqslant 0.5$ MeV. The calculations are based on the reconstructed differential energy dependences of the neutron flux density. As shown in the tables, the spectra reconstructed by each method from different input data do not vary by more than 20%.

The calculations thus show that there is satisfactory agreement between the MLM and SAND-II reconstruction programs, and so they can be recommended for processing the results from activation measurements.

TABLE 1

Detector Reaction Rates and Energy Ranges Corresponding to a 90% Contribution to the Reaction Rate

No.	Detector	Z = 6.5 cm		Z = 42.5 cm	
		A_i	Energy Range, MeV	A_i	Energy Range, MeV
1	$^{103}Rh(n, n')^{103m}Rh$	$6{,}10 \cdot 10^{-15}$	0,38—2,4	$1{,}33 \cdot 10^{-16}$	0,20—1,9
2	$^{115}In(n, n')^{115m}In$	$9{,}10 \cdot 10^{-16}$	0,72—3,5	$1{,}45 \cdot 10^{-17}$	0,69—3,7
3	$^{232}Th(n, f)$	$1{,}60 \cdot 10^{-16}$	1,2—5,5	$2{,}00 \cdot 10^{-16}$	1,2—7,8
4	$^{31}P(n, p)^{31}Si$	$3{,}50 \cdot 10^{-17}$	1,8—7,0	$4{,}90 \cdot 10^{-19}$	1,9—8,8
5	$^{32}S(n, p)^{32}P$	$6{,}80 \cdot 10^{-17}$	2,0—7,5	$9{,}60 \cdot 10^{-19}$	2,1—9,3
6	$^{35}Cl(n, \alpha)^{32}P$	$2{,}50 \cdot 10^{-17}$	3,1—8,7	$4{,}90 \cdot 10^{-19}$	3,4—10,0
7	$^{27}Al(n, p)^{27}Mg$	$3{,}60 \cdot 10^{-18}$	3,5—9,8	$9{,}40 \cdot 10^{-20}$	3,9—10,7
8	$^{56}Fe(n, p)^{56}Mn$	$1{,}10 \cdot 10^{-18}$	5,4—11,6	$3{,}80 \cdot 10^{-20}$	5,7—12,1
9	$^{24}Mg(n, p)^{24}Na$	$1{,}60 \cdot 10^{-18}$	6,6—11,9	$6{,}00 \cdot 10^{-20}$	6,7—12,2
10	$^{27}Al(n, \alpha)^{24}Na$	$8{,}25 \cdot 10^{-19}$	6,6—12,2	$3{,}30 \cdot 10^{-20}$	6,8—12,5

TABLE 2

Differential energy dependence of the neutron flux density $/\overline{\ }\ n/cm^2 \cdot s \cdot MeV\ \overline{\ }/$ behind shielding Z = 6.5 cm thick

E_n, MeV	SAND-II (sp. 58)	MLM $e^{-\mu E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT
0,5	$2{,}134 \cdot 10^{10}$	$1{,}23 \cdot 10^{10}$	$1{,}723 \cdot 10^{10}$	$1{,}67 \cdot 10^{10}$	$1{,}493 \cdot 10^{10}$	$1{,}45 \cdot 10^{10}$
0,6	$1{,}729 \cdot 10^{10}$	$1{,}30 \cdot 10^{10}$	$1{,}523 \cdot 10^{10}$	$1{,}49 \cdot 10^{10}$	$1{,}474 \cdot 10^{10}$	$1{,}45 \cdot 10^{10}$
0,7	$1{,}485 \cdot 10^{10}$	$1{,}31 \cdot 10^{10}$	$1{,}419 \cdot 10^{10}$	$1{,}38 \cdot 10^{10}$	$1{,}413 \cdot 10^{10}$	$1{,}41 \cdot 10^{10}$
0,8	$1{,}282 \cdot 10^{10}$	$1{,}33 \cdot 10^{10}$	$1{,}302 \cdot 10^{10}$	$1{,}28 \cdot 10^{10}$	$1{,}336 \cdot 10^{10}$	$1{,}36 \cdot 10^{10}$
0,9	$1{,}082 \cdot 10^{10}$	$1{,}29 \cdot 10^{10}$	$1{,}136 \cdot 10^{10}$	$1{,}16 \cdot 10^{10}$	$1{,}251 \cdot 10^{10}$	$1{,}28 \cdot 10^{10}$
1,0	$9{,}829 \cdot 10^{9}$	$1{,}18 \cdot 10^{10}$	$1{,}021 \cdot 10^{10}$	$1{,}05 \cdot 10^{10}$	$1{,}103 \cdot 10^{10}$	$1{,}14 \cdot 10^{10}$
1,2	$6{,}581 \cdot 10^{9}$	$6{,}66 \cdot 10^{9}$	$6{,}596 \cdot 10^{9}$	$6{,}66 \cdot 10^{9}$	$6{,}876 \cdot 10^{9}$	$6{,}92 \cdot 10^{9}$
1,4	$2{,}699 \cdot 10^{9}$	$2{,}33 \cdot 10^{9}$	$2{,}760 \cdot 10^{9}$	$2{,}90 \cdot 10^{9}$	$2{,}858 \cdot 10^{9}$	$2{,}84 \cdot 10^{9}$
1,6	$1{,}508 \cdot 10^{9}$	$1{,}29 \cdot 10^{9}$	$1{,}519 \cdot 10^{9}$	$1{,}49 \cdot 10^{9}$	$1{,}487 \cdot 10^{9}$	$1{,}47 \cdot 10^{9}$
1,8	$1{,}074 \cdot 10^{9}$	$9{,}17 \cdot 10^{8}$	$1{,}002 \cdot 10^{9}$	$9{,}82 \cdot 10^{8}$	$1{,}002 \cdot 10^{9}$	$9{,}87 \cdot 10^{8}$
2,0	$7{,}239 \cdot 10^{8}$	$6{,}04 \cdot 10^{8}$	$6{,}347 \cdot 10^{8}$	$6{,}02 \cdot 10^{8}$	$6{,}515 \cdot 10^{8}$	$6{,}13 \cdot 10^{8}$
2,5	$2{,}600 \cdot 10^{8}$	$2{,}49 \cdot 10^{8}$	$2{,}470 \cdot 10^{8}$	$2{,}29 \cdot 10^{8}$	$2{,}525 \cdot 10^{8}$	$2{,}33 \cdot 10^{8}$
3,0	$8{,}521 \cdot 10^{7}$	$1{,}34 \cdot 10^{8}$	$1{,}283 \cdot 10^{8}$	$1{,}32 \cdot 10^{8}$	$1{,}321 \cdot 10^{8}$	$1{,}33 \cdot 10^{8}$
3,5	$7{,}457 \cdot 10^{7}$	$8{,}83 \cdot 10^{7}$	$8{,}775 \cdot 10^{7}$	$9{,}04 \cdot 10^{7}$	$8{,}706 \cdot 10^{7}$	$8{,}86 \cdot 10^{7}$
4,0	$6{,}361 \cdot 10^{7}$	$6{,}36 \cdot 10^{7}$	$6{,}579 \cdot 10^{7}$	$7{,}10 \cdot 10^{7}$	$6{,}076 \cdot 10^{7}$	$6{,}34 \cdot 10^{7}$
4,5	$4{,}588 \cdot 10^{7}$	$4{,}09 \cdot 10^{7}$	$4{,}661 \cdot 10^{7}$	$5{,}17 \cdot 10^{7}$	$4{,}013 \cdot 10^{7}$	$4{,}20 \cdot 10^{7}$
5,0	$3{,}529 \cdot 10^{7}$	$3{,}00 \cdot 10^{7}$	$3{,}607 \cdot 10^{7}$	$3{,}71 \cdot 10^{7}$	$3{,}016 \cdot 10^{7}$	$3{,}06 \cdot 10^{7}$
5,5	$2{,}255 \cdot 10^{7}$	$2{,}07 \cdot 10^{7}$	$2{,}429 \cdot 10^{7}$	$2{,}46 \cdot 10^{7}$	$2{,}001 \cdot 10^{7}$	$2{,}03 \cdot 10^{7}$
6,0	$1{,}578 \cdot 10^{7}$	$1{,}51 \cdot 10^{7}$	$1{,}526 \cdot 10^{7}$	$1{,}44 \cdot 10^{7}$	$1{,}510 \cdot 10^{7}$	$1{,}51 \cdot 10^{7}$
6,5	$1{,}145 \cdot 10^{7}$	$1{,}16 \cdot 10^{7}$	$9{,}398 \cdot 10^{6}$	$7{,}09 \cdot 10^{6}$	$1{,}210 \cdot 10^{7}$	$1{,}20 \cdot 10^{7}$
7,0	$8{,}495 \cdot 10^{6}$	$8{,}62 \cdot 10^{6}$	$5{,}641 \cdot 10^{6}$	$4{,}40 \cdot 10^{6}$	$9{,}123 \cdot 10^{6}$	$9{,}01 \cdot 10^{6}$
7,5	$6{,}333 \cdot 10^{6}$	$6{,}35 \cdot 10^{6}$	$3{,}728 \cdot 10^{6}$	$2{,}97 \cdot 10^{6}$	$6{,}756 \cdot 10^{6}$	$6{,}69 \cdot 10^{6}$
8,0	$4{,}512 \cdot 10^{6}$	$4{,}56 \cdot 10^{6}$	$2{,}547 \cdot 10^{6}$	$2{,}01 \cdot 10^{6}$	$4{,}816 \cdot 10^{6}$	$4{,}77 \cdot 10^{6}$
8,5	$3{,}333 \cdot 10^{6}$	$3{,}33 \cdot 10^{6}$	$1{,}904 \cdot 10^{6}$	$1{,}65 \cdot 10^{6}$	$3{,}452 \cdot 10^{6}$	$3{,}43 \cdot 10^{6}$
9,0	$2{,}434 \cdot 10^{6}$	$2{,}39 \cdot 10^{6}$	$1{,}630 \cdot 10^{6}$	$1{,}39 \cdot 10^{6}$	$2{,}445 \cdot 10^{6}$	$2{,}44 \cdot 10^{6}$
9,5	$1{,}765 \cdot 10^{6}$	$1{,}69 \cdot 10^{6}$	$1{,}379 \cdot 10^{6}$	$1{,}22 \cdot 10^{6}$	$1{,}719 \cdot 10^{6}$	$1{,}72 \cdot 10^{6}$
10,0	$1{,}235 \cdot 10^{6}$	$1{,}19 \cdot 10^{6}$	$1{,}121 \cdot 10^{6}$	$1{,}05 \cdot 10^{6}$	$1{,}178 \cdot 10^{6}$	$1{,}18 \cdot 10^{6}$
10,5	$8{,}606 \cdot 10^{5}$	$8{,}29 \cdot 10^{5}$	$9{,}147 \cdot 10^{5}$	$9{,}24 \cdot 10^{5}$	$8{,}019 \cdot 10^{5}$	$8{,}05 \cdot 10^{5}$
11,0	$6{,}085 \cdot 10^{5}$	$5{,}83 \cdot 10^{5}$	$8{,}020 \cdot 10^{5}$	$8{,}42 \cdot 10^{5}$	$5{,}487 \cdot 10^{5}$	$5{,}52 \cdot 10^{5}$
11,5	$4{,}145 \cdot 10^{5}$	$4{,}06 \cdot 10^{5}$	$6{,}770 \cdot 10^{5}$	$7{,}56 \cdot 10^{5}$	$3{,}660 \cdot 10^{5}$	$3{,}68 \cdot 10^{5}$
12,0	$2{,}859 \cdot 10^{5}$	$2{,}82 \cdot 10^{5}$	$5{,}868 \cdot 10^{5}$	$6{,}93 \cdot 10^{5}$	$2{,}456 \cdot 10^{5}$	$2{,}47 \cdot 10^{5}$

TABLE 3

Differential energy dependence of neutron flux density
$[n/cm^2 \cdot s \cdot MeV]$ behind shielding Z= 42.5 cm thick

E_n, MeV	SAND-II (sp. 52)	MLM $e^{-\mu E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT
0,5	$4,732 \cdot 10^8$	$3,73 \cdot 10^8$	$5,214 \cdot 10^8$	$5,17 \cdot 10^8$	$4,933 \cdot 10^8$	$4,98 \cdot 10^8$
0,6	$4,138 \cdot 10^8$	$3,75 \cdot 10^8$	$4,383 \cdot 10^8$	$4,37 \cdot 10^8$	$4,488 \cdot 10^8$	$4,58 \cdot 10^8$
0,7	$3,591 \cdot 10^8$	$3,67 \cdot 10^8$	$3,817 \cdot 10^8$	$3,76 \cdot 10^8$	$3,903 \cdot 10^8$	$4,07 \cdot 10^8$
0,8	$3,054 \cdot 10^8$	$3,58 \cdot 10^8$	$3,276 \cdot 10^8$	$3,24 \cdot 10^8$	$3,367 \cdot 10^8$	$3,52 \cdot 10^8$
0,9	$2,410 \cdot 10^8$	$3,11 \cdot 10^8$	$2,700 \cdot 10^8$	$2,78 \cdot 10^8$	$2,940 \cdot 10^8$	$3,08 \cdot 10^8$
1,0	$2,102 \cdot 10^8$	$2,50 \cdot 10^8$	$2,190 \cdot 10^8$	$2,24 \cdot 10^8$	$2,300 \cdot 10^8$	$2,42 \cdot 10^8$
1,2	$1,073 \cdot 10^8$	$9,71 \cdot 10^7$	$1,079 \cdot 10^8$	$1,05 \cdot 10^8$	$1,106 \cdot 10^8$	$1,06 \cdot 10^8$
1,4	$3,449 \cdot 10^7$	$2,46 \cdot 10^7$	$3,165 \cdot 10^7$	$3,22 \cdot 10^7$	$3,334 \cdot 10^7$	$3,13 \cdot 10^7$
1,6	$1,630 \cdot 10^7$	$1,29 \cdot 10^7$	$1,522 \cdot 10^7$	$1,50 \cdot 10^7$	$1,537 \cdot 10^7$	$1,48 \cdot 10^7$
1,8	$1,028 \cdot 10^7$	$9,15 \cdot 10^6$	$9,629 \cdot 10^6$	$9,66 \cdot 10^6$	$9,955 \cdot 10^6$	$9,68 \cdot 10^6$
2,0	$6,285 \cdot 10^6$	$5,92 \cdot 10^6$	$6,096 \cdot 10^6$	$5,92 \cdot 10^6$	$6,461 \cdot 10^6$	$5,93 \cdot 10^6$
2,5	$2,468 \cdot 10^6$	$2,44 \cdot 10^6$	$2,624 \cdot 10^6$	$2,46 \cdot 10^6$	$2,704 \cdot 10^6$	$2,41 \cdot 10^6$
3,0	$1,296 \cdot 10^6$	$1,38 \cdot 10^6$	$1,345 \cdot 10^6$	$1,42 \cdot 10^6$	$1,373 \cdot 10^6$	$1,36 \cdot 10^6$
3,5	$9,749 \cdot 10^5$	$1,06 \cdot 10^6$	$1,057 \cdot 10^6$	$1,10 \cdot 10^6$	$9,978 \cdot 10^5$	$1,02 \cdot 10^6$
4,0	$7,299 \cdot 10^5$	$7,63 \cdot 10^5$	$8,202 \cdot 10^5$	$8,80 \cdot 10^5$	$7,001 \cdot 10^5$	$7,38 \cdot 10^5$
4,5	$6,016 \cdot 10^5$	$6,13 \cdot 10^5$	$6,917 \cdot 10^5$	$7,53 \cdot 10^5$	$5,360 \cdot 10^5$	$5,75 \cdot 10^6$
5,0	$5,526 \cdot 10^5$	$5,17 \cdot 10^5$	$6,552 \cdot 10^5$	$6,61 \cdot 10^5$	$4,813 \cdot 10^5$	$5,04 \cdot 10^5$
5,5	$4,502 \cdot 10^5$	$4,13 \cdot 10^5$	$5,256 \cdot 10^5$	$5,19 \cdot 10^5$	$3,862 \cdot 10^5$	$4,02 \cdot 10^5$
6,0	$3,587 \cdot 10^5$	$3,45 \cdot 10^5$	$3,729 \cdot 10^5$	$3,62 \cdot 10^5$	$3,472 \cdot 10^5$	$3,51 \cdot 10^5$
6,5	$2,946 \cdot 10^5$	$3,20 \cdot 10^5$	$2,557 \cdot 10^5$	$2,17 \cdot 10^5$	$3,428 \cdot 10^5$	$3,37 \cdot 10^5$
7,0	$2,462 \cdot 10^5$	$2,64 \cdot 10^5$	$1,721 \cdot 10^5$	$1,51 \cdot 10^5$	$2,962 \cdot 10^5$	$2,91 \cdot 10^5$
7,5	$2,055 \cdot 10^5$	$2,14 \cdot 10^5$	$1,244 \cdot 10^5$	$1,10 \cdot 10^5$	$2,420 \cdot 10^5$	$2,38 \cdot 10^5$
8,0	$1,661 \cdot 10^5$	$1,68 \cdot 10^5$	$9,197 \cdot 10^4$	$7,71 \cdot 10^4$	$1,885 \cdot 10^5$	$1,86 \cdot 10^5$
8,5	$1,404 \cdot 10^5$	$1,31 \cdot 10^5$	$7,269 \cdot 10^4$	$6,50 \cdot 10^4$	$1,405 \cdot 10^5$	$1,40 \cdot 10^5$
9,0	$1,133 \cdot 10^5$	$9,86 \cdot 10^4$	$6,449 \cdot 10^4$	$5,61 \cdot 10^4$	$1,023 \cdot 10^5$	$1,02 \cdot 10^5$
9,5	$8,229 \cdot 10^4$	$7,31 \cdot 10^4$	$5,587 \cdot 10^4$	$4,97 \cdot 10^4$	$7,329 \cdot 10^4$	$7,38 \cdot 10^4$
10,0	$5,775 \cdot 10^4$	$5,34 \cdot 10^4$	$4,636 \cdot 10^4$	$4,27 \cdot 10^4$	$5,130 \cdot 10^4$	$5,19 \cdot 10^4$
10,5	$4,043 \cdot 10^4$	$3,89 \cdot 10^4$	$3,849 \cdot 10^4$	$3,77 \cdot 10^4$	$3,547 \cdot 10^4$	$3,60 \cdot 10^4$
11,0	$2,873 \cdot 10^4$	$2,85 \cdot 10^4$	$3,431 \cdot 10^4$	$3,46 \cdot 10^4$	$2,452 \cdot 10^4$	$2,50 \cdot 10^4$
11,5	$1,969 \cdot 10^4$	$2,06 \cdot 10^4$	$2,947 \cdot 10^4$	$3,08 \cdot 10^4$	$1,657 \cdot 10^4$	$1,69 \cdot 10^4$
12,0	$1,368 \cdot 10^4$	$1,49 \cdot 10^4$	$2,598 \cdot 10^4$	$2,82 \cdot 10^4$	$1,122 \cdot 10^4$	$1,15 \cdot 10^4$

TABLE 4

Integral energy dependence of neutron flux density
$[n/cm^2 \cdot s]$ behind shielding Z = 6.5 cm thick

	SAND-II (sp. 58)	MLM $e^{-\mu E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT
$\Phi_{E \geq 3,0\ MeV}$	$1,741 \cdot 10^8$	$1,820 \cdot 10^8$	$1,932 \cdot 10^8$	$1,924 \cdot 10^8$	$1,868 \cdot 10^8$	$1,830 \cdot 10^8$
$\Phi_{E \geq 2,5\ MeV}$	$2,364 \cdot 10^8$	$2,496 \cdot 10^8$	$2,664 \cdot 10^8$	$2,593 \cdot 10^8$	$2,611 \cdot 10^8$	$2,508 \cdot 10^8$
$\Phi_{E \geq 1,0\ MeV}$	$4,398 \cdot 10^9$	$3,968 \cdot 10^9$	$4,431 \cdot 10^9$	$3,953 \cdot 10^9$	$4,615 \cdot 10^9$	$4,079 \cdot 10^9$
$\Phi_{E \geq 0,5\ MeV}$	$1,171 \cdot 10^{10}$	$1,039 \cdot 10^{10}$	$1,129 \cdot 10^{10}$	$1,061 \cdot 10^9$	$1,148 \cdot 10^{10}$	$1,088 \cdot 10^{10}$

TABLE 5

Integral energy dependence of neutron flux density
$/\overline{\ }\ n/cm^2 \cdot s\ \_/$ behind shielding Z = 42.5 cm thick

	SAND-II (sp. 52)	MLM $e^{-\lambda E}$	SAND-II 1/E	MLM 1/E	SAND-II WATT	MLM WATT·
$\Phi_{E\geq 3,0\ MeV}$	$2,923 \cdot 10^6$	$2,910 \cdot 10^6$	$3,067 \cdot 10^6$	$3,070 \cdot 10^6$	$2,895 \cdot 10^6$	$2,882 \cdot 10^6$
$\Phi_{E\geq 2,6\ MeV}$	$3,641 \cdot 10^6$	$3,611 \cdot 10^6$	$3,845 \cdot 10^6$	$3,789 \cdot 10^6$	$3,683 \cdot 10^6$	$3,577 \cdot 10^6$
$\Phi_{E\geq 1,0\ MeV}$	$7,091 \cdot 10^7$	$6,056 \cdot 10^7$	$7,129 \cdot 10^7$	$5,989 \cdot 10^7$	$7,375 \cdot 10^7$	$6,116 \cdot 10^7$
$\Phi_{E\geq 0,5\ MeV}$	$2,427 \cdot 10^6$	$2,332 \cdot 10^6$	$2,548 \cdot 10^6$	$2,378 \cdot 10^6$	$2,610 \cdot 10^6$	$2,504 \cdot 10^6$

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