International Atomic Energy Agency

INDC(CCP)-19/U

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

PLANNING AN OPTIMUM SET OF MICROSCOPIC EXPERIMENTS AND EVALUATIONS TO OBTAIN A GIVEN ACCURACY IN REACTOR PARAMETER CALCULATIONS

L.N. Usachev and Yu.G. Bobkov

(English translation of a Russian original.)

January 1972

IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

Translated from Russian

PLANNING AN OPTIMUM SET OF MICROSCOPIC EXPERIMENTS AND EVALUATIONS TO OBTAIN A GIVEN ACCURACY IN REACTOR PARAMETER CALCULATIONS

L.N. Usachev and Yu.G. Bobkov

ABSTRACT

The authors consider the accuracy required of microscopic nuclear data to ensure a given accuracy in the calculation of reactor parameters. They evolve a general method of allowing for the correlations of errors in microscopic quantities relating to different processes, energy groups and isotopes. The error is considered to consist of components differing in correlation properties. By dividing the error into components, it is possible to obtain simple formulae for linking these components with the required accuracy of a reactor parameter.

They further use "experiment planning" methods to obtain a mathematical formulation of the problem of determining the least costly complex of experiments which will ensure a given accuracy in the calculation of a reactor parameter. The solution to this problem is obtained in the form of simple formulae.

The requirements relating to all error components are calculated. It is shown that the requirements can be eased if the same method is used to measure neutron fluxes in experiments on fission and capture cross-sections.

The error in curve normalization is shown to be of particular importance, and the special role of evaluation in determining this error is stressed.

1. INTRODUCTION

(a) Variation of a reactor parameter as a function of variations in microscopic (group) quantities

The calculated value of each reactor parameter "C", for example the effective multiplication constant, breeding ratio, etc., depends on a large number of different microscopic quantities, such as the effective interaction cross-sections for different neutron energies, the number of secondary fission-neutrons and so on. Calculations are usually performed within the framework of a group model. The relative variations of the group quantities $\left(\frac{\delta\sigma}{\sigma}\right)_{\alpha ij}$, corresponding to a quantity of type "α" for isotope "i" in group j, define the relative variation of the reactor parameter δ C/C through the linear relation

$$\delta C/C = \sum_{\alpha i j} S_{\alpha i j} \left(\frac{\delta\sigma}{\sigma}\right)_{\alpha i j} \qquad (1)$$

The coefficients in this relation $S_{\alpha ij}$, known as sensitivity coefficients, are calculated in generalized perturbation theory [1].

(b) Formulation and solution of the problem of determining the necessary accuracies of nuclear constants in previous work

In order to determine the error in a reactor parameter "C", one needs to make an assumption regarding the sum of the contributions from the many errors entering into formula (1). If we consider these contributions as random quantities which are not correlated with one another, then, according to the rules of mathematical statistics, the dispersion or (to put it another way) the squared standard deviation of reactor parameter "C", i.e. D^2 ($D^2 \equiv (\overline{\delta C/C})^2$), will be expressed in terms of the dispersions of the microscopic group quantities $d^2_{\alpha ij}$ ($d^2_{\alpha ij} \equiv (\overline{\delta\sigma/\sigma})_{\alpha ij}$) in the following manner:

$$D^2 = \sum_{\alpha ij} S^2_{\alpha ij} d^2_{\alpha ij} \qquad (2)$$

This assumption was used by Moorhead [2], who obtained the sensitivity coefficients by direct calculation using a five-group model. Greebler, Hutchins and Linford [3] on the other hand suggested that it might be important to consider correlation of errors in the problem under discussion. They expressed the view that in real conditions almost every nuclear constant can have two or three correlation intervals over the whole of the energy axis. We might mention here that Moorhead [2] in fact used five correlation intervals since he performed a five-group calculation.

Zaritsky and Troyanov [4] studied the problem in great detail; they calculated a wide class of fast reactors, using generalized perturbation theory with an 18-group model, and performed comparative studies on the required accuracy of the constants for all these reactors. They have also provided formulae for the required accuracies of constants leading to a given accuracy in a reactor parameter, both for non-correlated constants and for constants correlated within a number of intervals. To distribute the error requirements for the different quantities in the right-hand side of formula (2), identical contributions from the different error sources are required, i.e. the following requirement is imposed:

$$d_{\alpha ij} = \frac{\text{const}}{|S_{\alpha ij}|} \qquad (3)$$

The latest work of Zaritsky, Nikolaev and Troyanov [5] offers a justification for requiring 1% accuracy in K_{eff} and 2% accuracy in the breeding ratio. Requirements are also formulated for the accuracy of a large number of microscopic quantities on the assumption of statistical independence of the error in each of the 18 groups. Here they depart to some extent from the principle of equal contributions by different constants (3), formulating intuitive considerations regarding comparable attainability of accuracy in the different constants by a method of selection and successive approximations.

Of special interest in this work is the idea of formulating accuracy requirements for the ratios of the quantities to standards such as $\bar{\nu}$ for ^{252}Cf and the fission cross-section of uranium-235, and also for the accuracy of the standards themselves. Such requirements have in fact been formulated, but they are based on the same assumption regarding non-correlation of errors in 18 groups.

(c) Criticism of previous work and the need for a correct approach to the analysis of error structure

Comparison of the results given in the papers referred to above [2-5] shows that in determinations of " required accuracy" the result is very much subject to the assumption made regarding correlation or non-correlation of errors. Greebler and co-workers estimate this effect to be a factor of 3-5. Furthermore, depending on whether correlations are [2, 3, 4] or are not [5] taken into account, the accuracy requirements for microconstants vary from values which cannot be satisfied within the foreseeable future to values which are already almost satisfied.

Since the solution of this problem must have a substantial influence on the definition of scientific policy, it is necessary to develop a more correct approach to the analysis of error correlations and to the more general problem of planning microscopic experiments as a whole.

In our opinion, the chief drawback of the papers mentioned above - a drawback which we are seeking to eliminate - is that the error in each quantity was regarded as an unstructured whole and considered to be either fully correlated with the errors of neighbouring quantities or fully non-correlated. On more careful examination, however, it becomes clear that one needs to take into account the structure of an error, the individual components of which differ from each other in correlation properties.

2. COMPONENTS OF THE RELATIVE ERROR IN A GROUP MICROSCOPIC QUANTITY AND THEIR RELATION TO THE ERROR IN THE REACTOR PARAMETER

(a) Notations and concepts

The relative error in the group microscopic quantity figuring in expression (1) is given above as $(\delta\sigma/\sigma)_{\alpha ij}$.

The subscripts are:

i - isotope number

j - group number

α - a characterization of the quantity which assumes values determined by the following table:

Quantity	Subscript in place of α
Average number of secondary fission neutrons	$\bar{\nu}$
Fission cross-section	f
Radiative capture cross-section	C
Fraction of fission spectrum in group "k"	χ_k
Reaction cross-section in group "K"	re_k
Transport cross-section	tr

The error in the quantity, as determined from the microscopic experiment, is characterized by a standard deviation "$d_{\alpha ij}$", the probability sense of which is given by the following formula:

$$d^2_{\alpha ij} = \overline{\left(\delta\sigma/\sigma\right)^2} \qquad (4)$$

where $(\delta\sigma/\delta)_{\alpha ij}$ is regarded as a random quantity and the bar denotes averaging over a large number of measurements. However, the standard deviation determined from expression (4), i.e. from the spread of experimental values in a specific experiment, is only a statistical component of the error. In fact, a process of fitting to some standard is usually applied in the experiment. The actual error must therefore include not only the statistical error but also the systematic error inherent in the method of fitting - that is, in our terminology, the normalization error - and also the error in the standard itself. Thus we have

$$\left(\delta\sigma/\sigma\right)_{\alpha ij} = \left(\delta\sigma/\sigma\right)^{stat}_{\alpha ij} + \left(\delta\sigma/\sigma\right)^{norm}_{\alpha i} f_j + \left(\delta\sigma/\sigma\right)^{stand} \qquad (5)$$

The sense of the vector f_j in formula (5) will be explained below. Usually, in calculating the total experimental error, all three above-mentioned error components are considered to be uncorrelated with each other and the squared standard deviations related to $(\delta\sigma/\sigma)$ by formula (4) are added up:

$$d_{\alpha ij}^2 = \left(d_{\alpha ij}^{stat}\right)^2 + \left(d_{\alpha i}^{norm}\right)^2 f_j^2 + \left(d^{stand}\right)^2 \qquad (6)$$

Here the statistical sense of $d_{\alpha ij}^{stat}$ and d^{stand} is clear. $d_{\alpha ij}^{stat}$ is determined in the experiment itself, while d^{stand} is taken from the nominal data on the standard or the standard method. The sense of $d_{\alpha i}^{norm}$ appears only when we consider some conceivable complex of experiments conducted by different methods, for which averaging can be performed in accordance with the definition in expression (4). Hence it is clear that the errors incurred in fitting or curve normalization can be evaluated experimentally only by analysing several experiments performed by independent methods, i.e. through an evaluation of nuclear data.

(b) Correlation properties of error components

Let us consider each of the three terms in the right-hand side of expression (5). The first term is purely statistical in nature and not correlated with other energy groups or with other types of process or with other isotopes. If within a single group there are n experimental points, each with a statistical error d, then

$$d_{\alpha ij}^{stat} = d/\sqrt{n} \qquad (7)$$

Expression (7) should be kept in view in discussing the permissible statistical error.

The third term is constant for all groups, substances and types of quantities, in the measurement of which the standard under consideration is used. This error component is thus fully correlated in the range where the standard is used. We shall mention two examples. If californium calibration is used in measuring the average number of secondary neutrons, $(\delta\sigma/\sigma)^{stand}$ is the error in the value of $\bar{\nu}$ for californium-252. If we consider a complex of measurements of different cross-sections in all of which the neutron flux is measured by the same method, $(\delta\sigma/\sigma)^{stand}$ denotes the systematic error in the flux measurement method.

The second term represents an error component correlated in different energy groups, i.e. the error in curve normalization. In cross-section measurements this error component can result, for example, from the error in determining the amount of the substance under study in the layer, from the systematic error in detecting events corresponding to the quantity being measured, or from the error in measuring the absolute neutron flux or in the standard cross-section from which the neutron flux was determined, if this error is not allowed for in the third term.

When $\bar{\nu}$ is measured with a californium standard, this error component can, more specifically, be due to differences in the hardness of the fission spectra for ^{252}Cf and the isotope under study, for such differences may result in different neutron detection efficiencies.

If there are several independent errors with identical correlation properties, they can be combined according to the ordinary rule of quadratic addition.

It is sometimes possible to introduce a calculated correction for the systematic error. Then the error remaining in the normalization will be the error in this correction. In such cases, we can draw conclusions concerning the behaviour of this error in relation to group number.

To describe this behaviour we introduce the vector f_j, which is equal to unity in the group with the maximum error and to zero or a negative quantity in groups where the systematic error under consideration should, from physical considerations, vanish or change sign.

It must be pointed out that neutron cross-sections and fluxes in different energy regions are measured by different methods. Thus as one approach we can select, in accordance with these regions, correlation intervals in each of which expression (5) is valid but which are not correlated with one another.

(c) Correlation of errors of the evaluated data

Data should be evaluated with due allowance for the correlation properties of the errors in the experimental data. Specifically, for example, when several sets of experimental data are available, the error in normalizing the cross-section curve should be determined from all of them. Thus, in the process of evaluation this error is determined and does not vanish, as Zaritsky and co-workers [5] in effect assume. Hence, in formulating the requirements to be imposed on the accuracy of evaluated and recommended data, one must consider the correlation properties of the errors as described above.

(d) Error in reactor parameter as a function of the error components in microquantities

It is clear from the foregoing that if single errors, $d_{\alpha ij}$, arose from error components in accordance with formula (6), they would be partially correlated. It is therefore not a correct procedure to go from formula (1) to formula (2).

The present work suggests a natural way of overcoming this difficulty. This consists in substituting into the relation derived from generalized perturbation theory (1) a component-wise representation of the error (5) and in grouping terms with identical $\delta\sigma/\sigma$:

$$\delta C/C = \sum_{\alpha ij} S_{\alpha ij}\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{stat}}_{\alpha ij} + \sum_{\alpha i}\left(\sum_j f_j S_{\alpha ij}\right)\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{norm}}_{\alpha i} + \left(\sum_{ij} S_{\nu ij}\right)\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{stand}}_{\nu} + \sum_{ij}\left(S_{fij} + S_{cij}\right)\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{stand}}_{\mathrm{flux}} \qquad (7a)$$

The first and second terms are obtained without any specific assumptions. In the case of the third, $\bar{\nu}$ is assumed to be measured for all fissionable isotopes over the whole energy region in accordance with the californium standard. The fourtn term is derived on the assumption that a single flux measurement method is used in measuring the radiative-capture and fission cross-sections for all isotopes where summation over the subscript i is implicit. In the relation obtained, each relative error is uncorrelated with the others. If we assume m correlation intervals (see the last paragraph of section (b)), the second and fourth terms on the right-hand side should be broken down into corresponding parts with independent relative errors:

$$\sum_{\alpha i}\left(\sum_j f_j S_{\alpha ij}\right)\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{norm}}_{\alpha i} \rightarrow \sum_{\alpha i}\sum_{K=1}^{m}\sum_{j=n_K}^{m_K}\left(\sum_j f_j S_{\alpha ij}\right)\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{norm}}_{\alpha i};\ \sum_{ij}\left(S_{fij} + S_{cij}\right)\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{stand}}_{\mathrm{flux}} \rightarrow \sum_{K=1}^{m}\sum_{i}\sum_{j=n_K}^{m_K}\left(S_{fij} + S_{cij}\right)\left(\frac{\delta\sigma}{\sigma}\right)^{\mathrm{stand}}_{K\,\mathrm{flux}} \qquad (7b)$$

where n_K and m_K are the numbers of the first and last groups of the K-th correlation interval. We rewrite the right-hand side of the relation obtained as a single sum from unity to N, where N is the number of independent errors, $^{\ell}(\delta\sigma/\sigma)$. The left-hand superscript ℓ takes values from 1 to N. Let us denote the coefficient before $^{\ell}(\delta\sigma/\sigma)$ by Z_ℓ. It is obvious that

$$Z_\ell \equiv \begin{cases} S_{\alpha ij} \\ \sum_{j=n_K}^{m_K} f_j S_{\alpha ij} \\ \sum_{ij} S_{\nu ij} \\ \sum_{i}\sum_{j=n_K}^{m_K}\left(S_{fij} + S_{cij}\right) \end{cases} \qquad K = 1, \ldots m \qquad (8)$$

$$\delta C/C = \sum_{\ell=1}^{N} Z_\ell\, {}^{\ell}(\delta\sigma/\sigma) \qquad (9)$$

Since all $^{\ell}(\delta\sigma/\sigma)$ are random non-correlated quantities, an expression for the dispersion of the reactor parameter is obtained in terms of the dispersions of the corresponding quantities:

$$D^2 = \sum_{\ell=1}^{N} Z_\ell^2 d_\ell^2 \qquad (10)$$

where $D^2 \equiv \overline{(\delta C/C)^2}$ and $d_\ell^2 \equiv \overline{^{\ell}(\delta\sigma/\sigma)^2}$ (see section 2a).

In relation (10), allowance for the correlation of the error components is indicated by the fact that the coefficients before the individual mean-square errors are squares of the sums of the sensitivity coefficients.

3. MINIMIZATION OF COSTS FOR THE WHOLE COMPLEX OF MICROSCOPIC EXPERIMENTS AND EVALUATIONS NEEDED TO ATTAIN A GIVEN ACCURACY IN REACTOR CALCULATIONS

(a) Theory and formulae

In this section we shall use the concept of statistical weight of an experiment or a complex of experiments, equal to the reciprocal of the root-mean-square error:

$$W_\ell = 1/d_\ell^2 \qquad (11)$$

As is often done in "experiment planning", the cost of the ℓ-th experiment is taken to be proportional to the statistical weight and equal to $\lambda_\ell W_\ell$, where λ_ℓ is a constant representing the cost of obtaining unit statistical weight in the determination of the ℓ-th quantity.

Accordingly, the total cost of a system of experiments for measuring microscopic constants which will ensure a given accuracy in the calculation of a reactor parameter is the sum of the costs attributable to each necessary experiment and complexes of experiments.

$$\text{Total cost} = \sum_{\ell=1}^{N} \lambda_\ell W_\ell \qquad (12)$$

We are interested in attaining, at minimum cost, a given accuracy in the reactor parameter, δ_o^2, which can also be expressed in terms of statistical weight if we substitute expression (11) in expression (10):

$$\delta_o^2 = D^2 = \sum_{\ell=1}^{N} Z_\ell^2/W_\ell = \sum_{\ell=1}^{N} Z_\ell^2 d_\ell^2 \qquad (13)$$

The problem of the minimum of expression (12), with the additional condition set by expression (13), is solved by the familiar method of indeterminate Lagrangian multipliers in which we seek the extremum of the following expression:

$$B = \sum_{\ell=1}^{N} \lambda_\ell W_\ell + \lambda \sum_{\ell=1}^{N} Z_\ell / W_\ell \qquad (13a)$$

where λ is an indeterminate Lagrangian multiplier.

Equating the partial derivatives with respect to W_ℓ to zero, we obtain a system of N equations:

$$\frac{\partial B}{\partial W_\ell} = 0 ; \quad \lambda_\ell - \lambda \frac{Z_\ell^2}{W_\ell^2} = 0 ; \quad \frac{1}{\lambda} = \frac{Z_\ell^2}{W_\ell^2 \lambda_\ell} = \frac{Z_\ell^2 d_\ell^2}{\lambda_\ell} \qquad (13b)$$

Excluding $1/\lambda$, we obtain N-1 equations:

$$d_\ell / d_k = \left(Z_k / Z_\ell \right)^{1/2} \left(\lambda_\ell / \lambda_k \right)^{1/4} \qquad (14)$$

Using this relation and expressing d_ℓ in terms of d_1 in expression (13), which is the N-th equation, we write

$$\delta_0^2 = d_1^2 Z_1^2 + d_1^2 \left(\frac{Z_1}{Z_2} \right) \left(\frac{\lambda_2}{\lambda_1} \right)^{1/2} Z_2^2 + \cdots + d_1^2 \left(\frac{Z_1}{Z_N} \right) \left(\frac{\lambda_N}{\lambda_1} \right)^{1/2} Z_N^2 \qquad (14a)$$

We determine d_1 from the last relation and the accuracies d_ℓ of all other experiments from relation (14).

If the calculated errors in some quantities are larger than the values assumed to have been attained, the calculation programme should have a block with the following functions. All such terms are identified and their contribution to the total error is calculated by formula $\sum_{d_\ell > d_\ell \text{ assum.}} Z_\ell^2 \cdot d_\ell^2 \text{ assum.}$. This contribution is deducted from δ_0^2 and then the whole procedure is repeated for the remaining terms. Provision should be made for iterations till full convergence of this process. We thus find the required accuracies for all quantities entering into the calculation which will satisfy the accuracy requirements for a reactor parameter at minimum cost.

(b) Determination of the relative cost of experiments on the basis of the hypothesis that experimenters have equal "ability to obtain funds"

In order to determine the relative cost of experiments, i.e. the ratios λ_ℓ / λ_k, we shall assume that identical amounts of money have been spent to obtain

statistical weights in all the experiments performed so far. In other words, we are assuming that the experimenters who have been engaged in making different measurements in different institutes and countries are men with an equal "ability to obtain funds" for experiments, and that the difference in the accuracy obtained derives from the comparative objective difficulties inherent in the experiments. Thus we have

$$\lambda_{\ell} W_{\ell} = \lambda_k W_k$$

Assigning the W_{ℓ}, W_k values attained so far, we obtain the relations

$$\lambda_{\ell} / \lambda_k = W_k / W_{\ell} = d_{\ell}^2 / d_k^2$$

We could also introduce a "coefficient of attention" in the quantity "k", viz. CAQ_k and, in order to determine $\lambda_{\ell} / \lambda_k$, use

$$\frac{\lambda_{\ell} W_{\ell}}{CAQ_{\ell}} = \frac{\lambda_k W_k}{CAQ_k} .$$

(c) Calculated required accuracies

The sensitivity coefficients are taken from Zaritsky and Troyanov [4] for a reactor using plutonium-239 and uranium-238 oxides and having a volume of 5000 litres.

The assumptions we have made as to accuracy attained in determining the relative cost of experiments, are indicated in the table below. Results corresponding to $K_{eff} = \pm 0.01$ are presented. These accuracies ensure a determination of breeding ratio to within ± 0.02.

(d) Discussion of results

The assumption that the errors are purely statistical leads to a rather low estimate of the necessary experimental accuracies. On this assumption, the accuracies that have been achieved already would satisfy the requirements.

Quantity		Assumption as to accuracy achieved, %		Sum $\Sigma Z^2 \times 10^4$ determining the energy-averaged permissible errors			Contribution of systematic error and error in standard to δ_o^2	Errors (in %) ensuring K_{eff} to within ± 1% averaged over the whole energy region, determined by the formula $d = \sqrt{\text{contribution}/\Sigma Z^2}$ **/					
									Error correlated over the whole region		Realistic variant, three correlation intervals		
		Statistical error component	Error in normalization or in the standard	12 non-correlated groups	Error correlated over the whole energy region	3 correlation intervals		Purely statistical error, %	Flux measured independently in each experiment	Single flux measurement method, d_{norm} or d_{stand}	Flux measured independently in each experiment	Single flux measurement method: d_{norm} or d_{stand}	Single flux measurement method: $\sqrt{d_{norm}^2 + d_{stand}^2}$
Fission cross-section	^{239}Pu	1	2	390	3850	1690	0.138	2.6	0.75	0.6	1.1	0.9	2.2
	^{238}U	1	2	28	66.5	66.5	0.018	3.5	2.0	1.6	2.0	1.6	2.6
Capture cross-section	^{239}Pu	2	10	3.8	31.2	21.5	0.062	17	5.5	4.4	6.7	5.4	5.7
	^{238}U	2	5	88	758	426	0.152	5.7	1.7	1.4	2.4	1.9	2.8
$\bar{\nu}$	^{239}Pu	0.5	1	750	7450	7450	0.096	1.6	0.36	0.36	0.36	0.36	0.5
	^{238}U	0.5	1	700	180	180	0.015	2	0.91	0.91	0.91	0.91	1
$\bar{\nu}$	^{252}Cf	-	1	-	10 000	10 000	0.112	-	0.33	0.33	0.33	0.33	-
Neutron flux		-	5	-	1400	507	0.208	-	-	1.2	-	2.0	-

Remarks:

*/ In not purely statistical variants $\delta_o^2 = 1$ is made up of the following contributions: 0.8 is accounted for by systematic errors and errors in standards, 0.1 by statistical errors and 0.1 is left for the contribution of errors in quantities not considered.

**/ In the non-flux and californium-standard variants, their contributions are redistributed to other quantities.

When we take into consideration the possibility of errors in the normalization of curves, i.e. systematic errors, the requirements at once become more severe and difficult to satisfy in the near future, especially in view of the accuracy of 0.7% demanded for the fission cross-section of plutonium and 1.7% for the capture cross-section of uranium-238. If the whole energy region is divided into three correlation intervals, $E_1 > 1.4$ MeV $> E_2 > 0.1$ MeV $> E_3$, the above requirements become slightly less stringent: 1.1% for the fission cross-section of plutonium and 2.4% for the capture cross-section of uranium-238. The errors mentioned also include those of absolute flux measurement and errors from other causes which lead to a systematic shift in the quantity of interest.

If the neutron flux is measured by a single method in experiments on capture and fission cross-sections, we obtain a correlation between the errors in the different cross-sections, which, unlike that between errors in neighbouring energy groups, appreciably reduces the accuracy requirements. Thus, in the case of the fission cross-section of ^{239}Pu, the accuracy now required for the two variants discussed, including flux, is 1.45 and 2.2%, respectively. In the case of the capture cross-section of ^{238}U these figures are 2.2 and 2.8%, respectively.

We consider that the assumption of three correlation intervals is realistic, i.e. that of the variants considered it gives the closest representation of the actual experimental situation.

It is for this case, therefore, that we carried out the following calculations. First, the accuracy assumed to have been attained gives $K_{eff} = \pm 1.8\%$. Second, a calculation performed on the basis of the accuracy requirements of Zaritsky and co-workers [5] gives $K_{eff} = \pm 1.5\%$ and not $\pm 1\%$ as they believed.

This shows that our accuracy requirements are, on average, 1.5 times more severe. The difference is not greater for the reason that, although no errors in normalization were assumed by Zaritsky (this is equivalent to assuming no correlation between errors in different groups), the correlation between errors due to ^{252}Cf standards and the uranium-235 cross-section were in fact taken into account.

CONCLUSIONS

The following conclusions can be drawn from the results. The accuracy requirements can be reduced by a rational choice of correlations in the

measurements. We should seek to correlate the capture and fission measurements for different isotopes, keeping in mind the different signs of the sensitivity coefficients. The same should also be done in the evaluation of nuclear data. But, at the same time, a great deal of work has yet to be carried out in order to satisfy these requirements. This implies, first of all, a need to measure the absolute neutron flux with an accuracy of 2%, the absolute value of $\bar{\nu}$ for ^{252}Cf with an accuracy of 0.33%, $\bar{\nu}$ for ^{239}Pu in relation to californium with an accuracy of 0.36% in normalization, and ^{238}U capture with a systematic error not exceeding 1.9%.

We must also point out the need for further analysis of the required accuracy of microscopic constants on the basis of the method developed above. Other isotopes and other cross-sections, apart from those considered here, will have to be studied. In the present work they were taken into account by reserving 0.1 from $\delta_o^2 = 1$. This is approximately true, as can be concluded from the results of Zaritsky and co-workers [5].

The formulation of requirements relating to evaluation work follows from everything that has been said.

Such work should analyse all the error components anticipated above and give evaluations of their magnitudes. Only if this is done will we be able to determine the error in a reactor parameter calculation due to a particular quantity evaluated, and hence the requirement for more refined measurement and evaluation of that quantity.

The most important error in the normalization of curves can be objectively determined only by analysing work carried out by different methods. The determination of this error is no less important than that of its average magnitude.

In conclusion, the authors wish to express their profound gratitude to M.F. Troyanov, B.D. Kuzminov, G.N. Smirenkin and V.A. Tolstikov for discussion of the work, and to A.N. Davletshin for his help in the calculations.

REFERENCES

[1] USACHEV, L.N. Atomn. Energ., 15 (1963) 472. USACHEV, L.N., ZARITSKY, S.M., Bjulleten' Informacionnogo Centra po Jadernym Dannym (Bulletin of the Nuclear Data Information Centre), No. 2, Atomizdat, Moscow (1965) 242. ZARITSKY, S.M., ibid., No. 6, (1969) 289.

[2] MOORHEAD, T.P., in Physics of Fast and Intermediate Reactors (Proc. Seminar Vienna, 1961) IAEA, Vienna (1962).

[3] GREEBLER, P., HUTCHINS, B.A., LINFORD, R.B., Nucl. Appl., 4 (1968) 297.

[4] ZARITSKY, S.M., TROYANOV, M.F., in Fizika jadernyh reaktorov (Physics of Nuclear Reactors) No. 2, Atomizdat, Moscow (1970) 168.

[5] ZARITSKY, S.M., NIKOLAEV, M.N., TROYANOV, M.F., "Potrebnosti v jadernyh dannyh dlja rasčeta bystryh reaktorov" (Nuclear data requirements for calculating fast reactors). Paper presented at the Conference on Neutron Physics, Kiev, May 1971.