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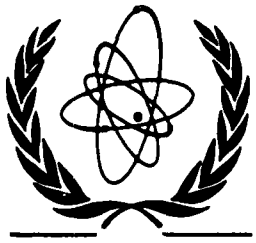

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PLANNING OF NEUTRON DATA EXPERIMENTS AND EVALUATIONS FOR REACTORS

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Institute of Physics and Power Engineering

Obninsk, 1974

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ABSTRACT

The authors describe a method of planning experiments and evaluations so as to achieve the accuracies required in the calculation of any number of reactor parameters. It is shown that the planning operation reduces to a multiparametric non-linear programming problem and various ways of solving this problem are considered. Calculations are performed of the accuracies of microscopic experiments ensuring accuracies of $\pm$ 1% and $\pm$ 2% respectively in the calculation of k_{eff} and the conversion ratio for a plutonium breeder both with and without allowance for integral experiments.

1. Introduction

At the present stage in the development of nuclear power engineering, pilot fast reactors are going into operation and work is proceeding on power engineering plans based on such reactors. However, the uncertainties in the field of nuclear data are such that fast reactor concepts may change, so that it is important for us to improve our knowledge in the nuclear data field still further. On the other hand, striving for the even-greater accuracy of nuclear data involves large investments in the development of experimental techniques. That is why methods of experiment planning should be applied in this area of science and technology. The proceedings of the First All-Union Conference on Neutron Emission Metrology contain a paper by us [1] where an account is given of the development of an approach to this question [2-4] and a solution offered to the problem of planning an optimum set of individual microscopic experiments so as to minimize their cost while achieving satisfactory accuracy in the calculation of one reactor parameter.

In the present paper we pose and solve the problem of minimizing the cost of a set of microscopic experiments while achieving satisfactory accuracy in the calculation of any number of reactor parameters. In addition,

the availability of information on any number of completed integral experiments is also taken into account. Some special approaches to the question of relaxing the accuracy requirements with regard to microscopic data through integral experiments have been touched on by the authors [5-7]. In principle, the same approach is employed in the United Kingdom [8, 9], but according to Rowlands without a formalized algorithm. In the present paper, this problem is posed and solved more rigorously.

2. Mathematical formulation of the problem

It has been shown [1] that the dispersion of a reactor parameter D_ℓ^2 is expressed in terms of the squares of the error components of individual microscopic nuclear data d_β^2 and the sensitivity coefficients $Z_{\beta\ell}$ as follows

$$D_\ell^2 = \sum_{\beta=1}^{N_1} Z_{\beta\ell}^2 d_\beta^2 \qquad (1)$$

It should be noted that the coefficients $Z_{\beta\ell}$ are the product of several transformations of the coefficients of the sensitivity of a reactor parameter to variations of the group constants. These transformations take into account the correlation characteristics of individual error components (for a more detailed treatment see Ref. [1]). The expression for the cost of experiments is written in the form $\sum_{\beta=1}^{N} \lambda_\beta / d_\beta^2$ (see Ref. [1]). If one also bears in mind that the unknown errors must have an upper limit governed by the accuracies achieved and a lower limit of zero, the problem of planning an optimum set of microscopic experiments and evaluations which will ensure the required accuracy "K" in the calculation of reactor parameters reduces to solving the following experimental problem:

$$\sum_{\beta=1}^{N} \lambda_\beta / d_\beta^2 \longrightarrow \text{MIN} \qquad (5A)$$

$$\sum_{\beta=1}^{N} Z_{\beta\ell}^2 d_\beta^2 \leq D_\ell^2 \qquad \ell = 1 \ldots L \qquad (5B)$$

$$0 < d_\beta^2 \leq d_{\beta_0}^2 \qquad (5C)$$

Let us now also take integral experiments into consideration. It can be shown [8, 9, 7] that, if simultaneous use is made of information on integral and microscopic measurements, the accuracy D_ℓ of calculations of a reactor parameter C_ℓ with sensitivity coefficients $\vec{Z}_\ell$ can be written as follows:

$$D_\ell^2 = \vec{Z}_\ell D(N+K) \vec{Z}_\ell^+ \tag{6}$$

where $$D(N+K) = \left(I - D(N)F^+\left(V+FDF^+\right)^{-1}F\right) D(N) \tag{7}$$

Here D(N) is the covariant matrix only of microscopic experiments, F - a matrix with the dimension (N*K) - represents the sensitivity coefficients of the integral experiments employed, and V is the matrix of the experimental errors of the integral experiments.

As shown in Ref. [1], the matrix D(N) can be made diagonal, the diagonal elements of the matrix being squares of the accuracies of the microscopic data.

Accordingly, the problem of planning a set of microscopic experiments when one has K integral ones, can be reduced to the following extreme problem:

$$\sum_{\beta=1}^{N} \lambda_\beta / d_\beta^2 \longrightarrow MiN \tag{8A}$$

$$\vec{Z}_\ell D(N+K) \vec{Z}_\ell^T \le D_\ell^2 \quad \ell = 1 \dots L \tag{8B}$$

$$0 < d_\beta^2 \le d_{\beta 0}^2 \tag{8C}$$

The desired accuracies d_β^2 appear in limitation (8B) as elements of diagonal matrix D(N).

With regard to problem (5), it is possible to prove the uniqueness of the solution and consider various special cases which greatly simplify the solution of the problem. This has not proved possible with regard to problem (8).

Problems (5) and (8) were solved by the "penalty" function method [11], which enables one to replace the conditional minimization of functions (8A) or (5A) by the unconditional minimization of some function φ, which is a superposition of functions (5A) or (8A) and of several functionals of limitations (B) and (C):

$$\Phi(d_\beta, r_p) = \sum_{\beta=1}^{N} \lambda_\beta / d_\beta^2 + \frac{1}{r_p}\left[\sum_{\ell=1}^{k}\left\{MiN\left[0, D_\ell^2 - \vec{Z}_\ell D(N+K)\vec{Z}_\ell^T\right]\right\}^2 + \sum_{\beta=1}^{N} MiN\left\{0, d_{\beta 0}^2 - d_\beta^2\right\}^2\right]$$

If one selects the sequence of r_p in such a way that $\lim_{p\to\infty} r_\ell = 0$, one can demonstrate [11] that the sequence of the vectors $\vec{d}_p^*$, which are the minimum points of the functions $\varphi(\vec{d}, r_p)$, has as its limit the vector $\vec{d}^*$, which is the solution of problem (8) - or problem (5).

For unconditional minimization of the corresponding functions we used the following methods: Newton's method with exact one-dimensional scanning; the convex simplex method; Cauchy's method with exact one-dimensional scanning; the Fletcher-Reeves (?) method with exact one-dimensional scanning; the Fletcher-Reeves (?) method with a quadratic approximation and one-dimensional scanning. Scanning was carried out in 96-parameter space with two limitations. Newton's method with exact one-dimensional scanning proved to be the most effective for solving problem (5). Using a M-222 computer, with arbitrary selection of the initial point we needed 50 minutes to apply this method. The Fletcher-Reeves (?) method with a quadratic approximation and one-dimensional scanning proved to be the most effective for solving problem (8). We used 26 integral experiments (see Table 2) and took 3.5 hours with the M-222 computer. An increase in the number of limitations does not for practical purposes increase the amount of computer time needed.

Results of the calculations

We considered the model of a fast reactor with a composition and dimensions corresponding to a capacity of about 1000 MW(e) and with fuel in the form of a mixture of ^{238}U and ^{239}Pu oxides containing higher isotopes. This model is described in greater detail in Ref. [10]. The limitations consist in the requirement that the conversion ratio be predicted to within $\pm$ 2% and k_{eff} to within $\pm$ 1%.

We present in Table 1 the components of the errors in the principal nuclear quantities completely correlated in the energy intervals indicated in the table. The integral experiments employed with the accuracies ascribed to them are shown in Table 2.

In the columns with the heading "V" (and in the row designated by "V") we give the accuracy values taken by us, as those attained so far; in the columns with the headings "I" and "II" (and in the rows designated by "I" and "II") we give those permissible error values for problems without and with integral experiments respectively which satisfy both limitations; in the columns with the headings "III" and "IV" (and in the rows designated by "III" and "IV") we give those permissible error values for problems without and with integral experiments respectively which satisfy only the conversion ratio accuracy requirement.

The meaning of the two latter columns is that the possibility of employing integral criticality experiments for evaluation purposes (?) will reduce the accuracy requirements as regards k_{eff}, so that these two columns will determine the accuracy requirements as regards nuclear data for fast reactors in general.

It is worth examining the costs (in arbitrary units) of the combinations of microscopic experiments corresponding to the five sets of errors: V - 0.04, IV - 0.08, III - 0.12, II - 0.14, I - 0.18.

As can be seen by comparing these figures, the integral experiments employed by us reduce the accuracies required in microscopic experiments only by a third in cost terms.

It is hoped that more informative integral experiments can be found, performed and evaluated.

Thus, final conclusions regarding the required accuracies of microscopic data remain to be reached, with the approach described in this paper.

Table 1

Energy interval (MeV)		0,8< E <10					0,1< E <0,8					0< E <0,1				
Quantity \ Variant		I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
α	Pu 239	50	50	41	41	50	9,5	10	6,5	6,7	15	3,7	5,0	2,5	3,6	10
σ_f	Pu 239	2,6	4,0	6,0	10	10	1,3	2,3	4,0	6,0	7	1,1	2,0	4,0	4,0	7
ν_f	Pu 239	1,2	1,2	1,5	1,9	3	0,4	0,7	0,5	0,9	1	0,5	0,8	0,7	1,2	2
σ_c	U 238	9,3	10	19	19	20	2,8	6,0	4,3	4,7	10	2,2	4,0	2,6	4,4	15
σ_f	U 238	1,8	3,4	2,1	2,6	5										
ν_f	U 238	1,0	2,5	1,3	1,7	3										
σ_c	steel	20	20	25	25	50	15	18	17	18	30	11	15	12	13	30
σ_c	Pu 240	45	45	50	50	50	14	15	17	17	30	6,5	7,1	9	9	20
σ_f	Pu 240	3,5	5,0	4,4	6,5	7	5,3	7,0	6,6	6,6	7	7,0	7,0	7,0	7,0	7
ν_f	Pu 240	2,0	2,1	2,4	2,5	3	3,0	3,0	3,0	3,0	3	3,0	3,0	3,0	3,0	3
σ_f	Pu 241	10	10	10	10	10	5	5,4	6,2	6,2	10	3,7	3,8	4,5	5,0	15
ν_f	Pu 241	4,0	4,0	4,0	4,0	4	2,3	2,3	2,9	3,0	3	1,2	1,3	1,5	1,6	2
	Flux	1,3	1,7	2,0	2,7	6	1,1	1,8	2,5	2,7	3	2,0	3,0	2,1	2,5	4
σ_c	fragments	50	50	50	50	50	14	16	17	17	30	7,0	8,0	9,3	10	30

Required accuracy ν_{Cf} 252 - 0,3%

Continuation of Table 1

Energy interval (MeV) / Variant	I0,5-6	6-4,5	4,5-2,5	2,5-I,4	I,4-0,8	0,8-0,4	0,4-0,2
I	8,3	7,4	I6,4	3,0	2,7	6,6	6,5
II	8,6	8,0	I8	3,5	3,2	6,9	6,6
III	I0	9,3	20	3,9	2,6	I7,0	7,0
IV	I0	9,5	20	4,5	I0	7	7
V	30	20	20	I5	I0	7	7

Table 2

Integral experiments employed

Type of experiment	Accuracy %	Type of experiment	Accuracy %	Type of experiment	Accuracy %
BFS-26		BFS-27		α_9	10
f_{a10}/f_5	4	f_{C12}/f_5	4	α_5	10
f_{C12}/f_5	4	BFS-28		f_{a10}/f_5	3
BFS-27		F8/F5	4	f_{C12}/f_5	3
F8/F5	3	C8/F5	4	f_9/f_5	3
F9/F5	3	F9/F5	4		
C8/F5	6	f_9/f_5	3	ZPR-III-48	
α_9	10	f_{a10}/f_5	3	F8/F5	3
α_5	10			F40/F5	3
		BFS-30		F9/F5	3
f_{a10}/f_5	3	F8/F5	3		
f_9/f_5	3	F9/F5	3		

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