International Atomic Energy Agency

INDC(CCP)-17/U

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

NUCLEAR DATA REQUIREMENTS FOR THE CALCULATION OF FAST REACTORS

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(English translation of a Russian original.)

December 1971

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

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ABSTRACT

Owing to the need for accuracy in calculating the doubling time ($\pm$ 10%), K_{eff} ($\pm$ 1%) and breeding ratio ($\pm$ 2%) of large plutonium breeders, accuracy requirements have been formulated for such evaluated nuclear data used in compiling group constants as σ_f for ^{235}U, ν_f for ^{252}Cf, α for ^{239}Pu, the cross-section ratios $\sigma_c^i/\sigma_f^{235}$, $\sigma_f^i/\sigma_f^{235}$, the cross-section for inelastic removal below the fission threshold of ^{238}U, etc.

1. INTRODUCTION

The purpose of this paper is to establish what should be the accuracy of the nuclear constants recommended for fast reactor calculations, assuming that the required accuracy of calculation of the reactor characteristics is given. It is also assumed that, in assessing the recommended values of the constants, information obtained from integral reactor experiments is not used.

The accuracy of evaluated nuclear data is governed by the number, accuracy and scatter of the results of the differential measurements used in the evaluation. The strict determination of the accuracy of evaluated constants, particularly in cases when the results of various authors differ from each other much more than might be expected from the errors attributed to these data, is a matter which has not been finally settled, and we do not propose to examine it here. In putting forward requirements for the accuracy of evaluated constants, we in effect indicate the limits within which must fall the results of several independent measurements arrived at by different methods.

The analysis of the sensitivity of the results of reactor calculations to changes in the nuclear constants is fundamental to the evaluation of the required accuracy. This analysis was made by means of a generalized perturbation theory [1] for fast plutonium breeders with metal, carbide and oxide fuel intended for 600-1000 MW nuclear power stations [2].

2. ACCURACY REQUIREMENTS IN THE CALCULATION OF THE PHYSICAL CHARACTERISTICS OF A FAST POWER REACTOR

The uncertainty of nuclear data and its possible consequences were analysed at the Helsinki Conference [3]. The analysis revealed that the existing uncertainty of nuclear data leads to an error in calculating the fuel component of the electric power cost of ± 0.013 cent/kWh, which is about 3% of the total cost. Such uncertainty in the estimates of the total electric power cost is not excessive, since one can scarcely demand better than about 5% accuracy in economic evaluations in general. Thus, having established a reasonable admissible margin of error in the determination of the fuel component, we cannot lay down new requirements in respect of the accuracy of nuclear data determination and evaluation. Clearly, the uncertainty of nuclear data can affect not only the fuel but also the capital cost component thanks to the need to provide various design features in order to compensate for possible mistakes in the calculations. Furthermore, errors in calculation can lead not only to errors in the fuel load and the plutonium output but to a reduction in reactor power, at least until the mistake is corrected. However, it is very difficult to link these factors with the uncertainty of nuclear data.

We put forward accuracy requirements for nuclear data on the basis of the accuracy necessary in calculating the natural parameters of the fuel cycle: the uranium consumption for power generation and the doubling time T_2. Both these quantities are directly connected with the fuel load and the breeding ratio.

From the point of view of the utilization of natural resources of nuclear fuel, it is desirable that the characteristics of fast reactors should be such that atomic power generation can proceed using cheap uranium only. V.V. Orlov has shown that if fast reactors have a doubling time of 6–8 years, then with a nuclear power programme embodying thermal (water-moderated and -cooled) and fast reactors at an asymptotic rate of 8%, cheap uranium reserves would suffice. Thus, an average doubling time of about seven years will be required of future fast reactors, and the accuracy of its calculational prediction must be of the order of 10%.

On this basis we can state the accuracy requirements for the calculation of such reactor characteristics as K_{eff} and the breeding ratio BR. In fact,

$$T_2 \cong A \frac{G}{BR-1},$$

where A = constant and G = reactor loading; the error then is

$$\frac{\Delta T_2}{T_2} = \frac{\Delta G}{G} + \frac{\Delta BR}{BR} \Big/ \frac{BR}{BR-1} \Big/ \cong$$

$$\cong 2 \frac{\Delta K_{eff}}{K_{eff}} + \frac{\Delta BR}{BR} \Big/ \frac{BR}{BR-1} \Big/ .$$

This expression leaves the relationship between the permissible relative errors in K_{eff} and BR uncertain, and in order to establish this relationship additional considerations are needed.

In large fast reactors a K_{eff} error of 1% is on the verge of the possible from the point of view of its being offset by a change in the number of bundles compared to the design number or through compensation by the control devices. Even in the BN-350 reactor a ΔK_{eff} of 1% calls for a 5-6% change in the number of bundles. In larger reactors the volume changes needed to compensate for the error will be even greater. In the BN-600 reactor, for example, a K_{eff} error of 1% can shorten the operating time between recharging by 20-30%. These considerations justify a requirement that the accuracy of the K_{eff} calculation should be not worse than 1%. Then, for fast reactors with ceramic fuel and BR = 1.3-1.5 the required accuracy of the BR calculation is 1.8-2.7%.

The use of these particular values as criteria governing the accuracy requirements for nuclear constants is justified if the uncertainty of the reactor composition results in a smaller error in the K_{eff} and BR calculation.

To evaluate the accuracy requirement for knowledge of the composition of the reactor it was assumed that the uncertainty would give an error in K_{eff} of 0.5% and in BR of 1%. It was found that the averaged reactor composition must then be known with the following degree of accuracy:

Fuel loading (UO_2 + PuO_2)	- 0.8%
Plutonium concentration	- 0.4%
Fragment content	- 10%
Steel content	- 5%
Sodium content	- 7%

These requirements are considered to be met in view of the large numbers of fuel elements and bundles loaded into the reactor. The composition of individual bundles may fluctuate within fairly wide limits, but the average composition can be known with the necessary accuracy.

Therefore, as criteria for formulating accuracy requirements in respect of nuclear data we accept a permissible calculational error of:

$$\Delta K_{eff}/K_{eff} \lesssim \pm 1\%$$

$$\Delta BR/BR \lesssim \pm 2\%$$

which enables us to predict the doubling time with an accuracy of $\pm$ 10%.

3. EVALUATION OF THE REQUISITE ACCURACY OF NUCLEAR DATA

The matter of which measured nuclear data are the subject of accuracy requirements and of what these requirements* is governed by the way in which the recommended values for the group constants directly appearing in the reactor equations are derived from these nuclear data. We work out our requirements on the basis of the following scheme for defining the constants required for the diffusion calculation of the reactor (the customary notation is used, with i = the isotope index):

$$\sigma_c^i(E) = \sigma_f^{235}(E) \cdot z_c^i(E),$$
$$\sigma_c^{239}(E) = \alpha^{239}(E) \cdot \sigma_f^{235}(E) \cdot z_f^{239}(E),$$
$$\sigma_f^i(E) = \sigma_f^{235}(E) \cdot z_f^i(E),$$
$$\nu_f^i(E) = \nu_f^{Cf\text{-}252} \left(\nu_o^i / \nu_f^{Cf\text{-}252}\right) \left(\nu_f^i(E)/\nu_o^i\right),$$
$$\sigma_{tr}^i(E) = \sigma_{tot}^i(E) - \int M_e^i(E)\, \sigma_e^i(E),$$

* are,

and the elastic slowing-down cross-section $\sigma_{z(e)} = \xi\sigma_e/\Delta U$. Here $\sigma_f^{235}(E)$, $\tau_c^i(E) = \sigma_c^i(E)/\sigma_f^{235}(E)$, $\tau_f^i(E) = \sigma_f^i(E)/\sigma_f^{235}(E)$, $\sigma_{tot}^i(E)$, $\nu_f^{252}Cf$, $\nu_\sigma^i/\nu_f^{252}Cf$ (ν_o^i - is the reference value of ν_f^i), and $\nu_f^i(E)/\nu_o^i$ and $\mu_e^i(E)$ are quantities which can be measured (and in fact usually are measured) in independent experiments. We assume that the evaluated values of these quantities are defined independently for each energy group interval [4]. It should be noted that the existence of a correlation between the errors in one and the same constant in different groups will call for rather more stringent requirements regarding the accuracy of the nuclear data. Finally, we consider that the cross-sections for inelastic transfer from one group to another are defined on the basis of evaluated values of the effective temperature T_{in}^i of the inelastically scattered neutron spectrum and the cross-section for removal below the fission threshold of ^{238}U, $\sigma_{in,8}^i$ and under the fission threshold of ^{237}Np, $\sigma_{in,7}^i$.

It is difficult to make a final judgment regarding the distribution of error in the evaluated data, particularly if they are obtained from the results of several independent measurements. We shall regard this distribution as normal.

Obviously, the greater the influence of a variation in a constant on the results of a reactor calculation, the more accurately must the constant be known. From the point of view of the reliability of the calculational prediction of a reactor's characteristics, the most acceptable requirement is that the greatest possible variation in each constant, i.e. variation to the fullest extent of its permissible error, should result in the same change in the calculational characteristics of the reactor. Hence

$$d_\gamma^x = \frac{D_x}{\sqrt{n}} \cdot \frac{1}{/ x_\gamma /}$$

where D_x = the necessary accuracy in the calculation of characteristic x, d_γ^x = the required accuracy of the constant γ, n = the number of independent sources of error in the calculation (of independent constants whose accuracy requirements are put forward) and x_γ = the "efficiency" of γ in relation to x, i.e. a quantitative measure of the sensitivity of the calculation of x to a change in γ, which it is convenient to define as

$$x_\gamma = (\partial x/\partial \gamma)\ (\gamma/x)\ .$$

The efficiencies x_γ are calculated by means of a generalized perturbation theory [2].

In reckoning the sources of error n we should take account only of those which can make a real contribution to the total error. Several iterations can be carried out for this purpose. Having defined n in the first approximation and having calculated the total d_γ^x we must then exclude those constants whose genuinely achieved accuracy is known to be greater than the requirements established. The number of the remaining constants is then counted and new accuracy requirements are fixed for them which, thanks to the reduction of n, are less stringent than the previous ones. The process is repeated until d_γ^x ceases to change.

The results of evaluating d_γ^x in this way are given in Table 1. Only those requirements are given which are higher than the level of accuracy achieved at present. These are the requirements which are the most acceptable from the point of view of the reactor physicist since for all constants $d_\gamma^x \sim 1/|x_\gamma|$. However, it is obvious that many of these requirements can scarcely be regarded as realistic at the present time.

Accuracy requirements for constants that are more reasonable from the point of view of the experimenter and the evaluator but less satisfactory for the reactor physicist can be obtained if we abandon the condition $d_\gamma^x \sim 1/|x_\gamma|$ and try to offset the lowering of the accuracy requirements for some constants by more stringent but realistic ones regarding the accuracy of others, so that the overall calculational accuracy remains unaffected. One of the possible alternatives for such requirements is presented in Table 2. Clearly, even these requirements are very rigorous: the present accuracy of nuclear data is probably two or three times less good.

It should be pointed out that the accuracy requirements put forward for nuclear data relate to cross-sections in which corrections for resonance self-shielding have already been made. The values of these corrections are determined by the resonance self-shielding factors [4]. The accuracy of the knowledge of these factors (governed by the accuracy of the knowledge of the cross-section structure) must be such that the product of an average cross-section measured on a thin sample and the self-shielding factor is known with the degree of accuracy shown in Table 1 or 2. It follows from this that in the resonance region of energies the

accuracy requirements for the average cross-sections and the self-shielding factors must be 1.5 times higher than those indicated. Meeting the accuracy requirements for self-shielding factors may present special experimental difficulties, since these factors are largely determined by the value of the cross-section on the "tails" of the resonance and in the inter-resonance regions. In the unresolved resonance region these requirements can apparently be satisfied only in experiments involving passage through very thick samples [5].

The accuracy requirements for evaluated nuclear data can be lowered if the results of analysis of integral reactor experiments are taken into account in the choice of constants recommended for reactor calculations.

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Table 1 Accuracy requirements for evaluated nuclear data derived under conditions of an equal contribution by the permissible error of each constant to the error in the calculation of K_{eff} (upper figure) and BR (lower figure), ± %%

E_n	6,5	4	2,5	I,4	0,8	0,4	0,2	0,I MeV	46,5	2I,5	I0	2,I5	0,465	0,I keV
σ_f^{235}	7 I0	3 4	I,5 2	4 I0	2 8	2 8	2 7	4 6	6 9	I3 I6	25 I6	30 I6		
α^{239}					55 20	30 I0	20 I0	I5 6	I2 4	I2 4	I4 5	II 5		20 I0
τ_f^{239}		8 30	4 I6	3 I4	I,5 9	I,5 I0	I,3 I2	I,3 30	I,5 26	2 I4	3 I3	3 20		9 35
$\nu_f^{239}(E)/\nu_o^{239}$			2,4 2,7	2,I 2,3	I,I I,2	0,9 I,0	0,9 I,0	0,9 0,9	I,0 I,I	I,4 I,5	I,9 2	I,8 2		4 4
τ_c^{238}				I2 60	6 25	4 I6	3 9	2,5 5	2,5 5	2,5 5	3 5	4 5		
τ_f^{238}		4 4	2,5 2,5											
$\nu_f^{238}(E)/\nu_o^{238}$		2,5 2,5	I,5 I,5											
τ_c^{Fe}							40 30	35 30	35 30	50 40	50 40	35 30		
σ_{tot}^{Fe}								60 I0	30 I0					
τ_c fragments								40 45	40 50	40 50	30 40	25 35		40 85
Γ_γ^{Na}											I00 80			
Γ_n^{Na}											8 8			
σ_{tot}^{Na}								30 I5						
ν_f^{Cf-252}	0,I0 0,I2	$\sigma_{in,8}^{239}$	40 45	$\frac{\nu_o^{238}}{\nu_f^{Cf}}$	0,9 0,8	$\sigma_{in,7}^{238}$	I2 60	$\sigma_{in,8}^{Na}$	I5 20	$\sigma_{in,8}^{Fe}$	3 4	$\sigma_{in,8}^{frag.}$		30 45
$\frac{\nu_o^{239}}{\nu_f^{Cf}}$	0,I2 0,I3	$\sigma_{in,7}^{239}$	80 250	$\sigma_{in,8}^{238}$	2,5 2,5	T_{in}^{238}	5 5	T_{in}^{Na}	I5 20	T_{in}^{Fe}	4 5			

Table 2 A more realistic alternative for the accuracy requirements for evaluated nuclear data

Constant	Energy region ΔE_n	Required accuracy*/ ± %	Contribution to the error in the calculation, %	
			K_{eff}	BR
σ_f^{235}	0,5 keV – 7 MeV	3	0,35	0,38
ν_f^{Cf-252}		0,5	0,50	0,89
α^{239}	0,1кэв–0,8мэв	7	0,14	0,70
$\sigma_f^{239}/\sigma_f^{235}$	0,1кэв–4 мэв	2	0,36	0,10
$\nu_{f(E)}^{239}/\nu_0^{239}$	0,1кэв–2,5мэв	0,7	0,19	0,34
ν_0^{239}/ν_f^{Cf}		0,5	0,42	0,77
$\sigma_{in,8}^{239}$		10	0,03	0,05
$\sigma_{in,7}^{239}$		10	0,01	0,02
$\sigma_c^{238}/\sigma_f^{235}$	0,5кэв–1,4мэв	3	0,28	0,27
$\sigma_f^{238}/\sigma_f^{235}$	1,4мэв–4 мэв	3	0,15	0,29
$\nu_f^{238(E)}/\nu_0^{238}$	1,4мэв–4 мэв	0,7	0,05	0,11
ν_0^{238}/ν_f^{Cf}		0,7	0,08	0,16
$\sigma_{in,8}^{238}$		5	0,20	0,38
$\sigma_{in,7}^{238}$		5	0,04	0,07
T_{in}^{238}		5	0,1	0,2
$\sigma_c^{Fe}/\sigma_f^{235}$	0,5кэв–200кэв	10	0,06	0,14
σ_{tot}^{Fe}	20кэв– 100кэв	5	0,02	0,10
$\sigma_{in,8}^{Fe}$		5	0,05	0,10
T_{in}^{Fe}		5	0,13	0,20
$\sigma_c^{frag}/\sigma_f^{235}$	0,1кэв–100кэв	20	0,14	0,22
$\sigma_{in,8}^{frag}$		30	0,08	0,13
Γ_γ^{Na}	2,15кэв–10кэв	20	0,02	0,04
Γ_n^{Na}	2,15кэв–10кэв	5	0,06	0,13
σ_{tot}^{Na}	50кэв –100кэв	5	0,02	0,06
$\sigma_{in,8}^{Na}$		5	0,03	0,06
T_{in}^{Na}		5	0,03	0,06
		Total	± 1 %	±1,6%

*/ For each group interval [4] in the ΔE_n region.