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COMPARISON OF CALCULATIONS OF STANDARD FAST REACTORS
(using the Baker model)

A.I. Voropaev, A.A. Van'kov, A.M. Tsybulya

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ABSTRACT

The results of calculations of standard fast reactors performed in several laboratories with different sets of constants (OSKAR-75, BNAB-M, CARNAVAL-IV, FD-5, KFKINR, ENDF/B-IV) are compared.

1. Calculation model

The one-dimensional calculation model for a "standard" reactor was developed at the suggestion of the IAEA for comparing calculations of parameters determining the criticality and conversion ratio of fast reactors being designed in various countries [1]. The publication in 1971 of the results of this comparison (17 laboratories from 10 countries) served as a stimulus to international co-operation in the field of fast reactor physics. In 1975 the Institute of Physics and Power Engineering at Obninsk, USSR, approached a number of laboratories with the proposal that these calculations be repeated, using the specification proposed in Ref. [1]. The composition and dimensions of the model in question are given in Table 1. Three variants were proposed for the calculations:

A. Fuel consists of ^{239}Pu and ^{238}U;

B. Fuel consists of ^{239}Pu, ^{238}U and fission fragments ($\rho_{fp} = 0.0372 \times 10^{24}$ nucl/cm^3);

C. Fuel consists of ^{239}Pu, ^{240}Pu, ^{238}U and fission fragments ($\rho_{fp} = 0.0372 \times 10^{24}$ nucl/cm^3, $(^{239}Pu):(^{240}Pu) = 1:0.5$).

The temperature of the medium = 300°K. The reactor calculation is performed in the diffusion approximation. In the calculations criticality ($0.999 \leq K_{eff} \leq 1.001$) is obtained by variation of the enrichment. The external boundary conditions correspond to a vacuum behind the breeding blanket.

Table 1

Composition (10^{-24} nucl/cm^3) and dimensions of a spherical model of a reactor

Isotope	Core	Shield
Pu + U + FP	0,0072	-
239 Pu	-	0,00012
238 U	-	0,012
Ni	0,00088	0,00088
Fe	0,00814	0,00814
Cr	0,00198	0,00198
Na	0,0123	0,0069
O	0,0144	0,024
Dimensions of the zones (cm)	R =84,196	d =45,72
Recommended number of calculation zones ΔR (cm)	14 6,014	8 5,715

2. Characteristics of the calculations

A. Institute of Physics and Power Engineering (FEI), Obninsk, USSR

Below are given the results of three calculations:

(a) Calculations based on the BNAB-70 system of constants which is a modification of the well-known system of I.I. Bondarenko [2]. The constants for ^{238}U, ^{235}U and ^{239}Pu correspond to the 1970 evaluations. The data for all other isotopes correspond to the earlier evaluations in 1964. The BNAB-70 system of constants was widely used in the USSR in the design of reactors with uranium fuel (BOR-60, BN-350, BN-600). As experience of start-up and initial operation of the BN-350 reactor has shown, its basic characteristics were predicted with a satisfactory degree of accuracy. This is largely due to the fact that the system of constants in question was optimized on the basis of the results of a large number of experiments on critical assemblies with a uranium loading. However, we expect that prediction of the parameters of large breeders on the basis of the BNAB-70 constants will be much poorer [3-5].

The results of the calculations presented here are taken from Ref. [6]. They were obtained by applying the M-26 unidimensional set which employs the formalism of I.I. Bondarenko [2] in the calculation of the constants. The parabolic interpolation of the integral fluxes in the core and the shield was used to find the correction for the slowing-down cross-section. The fission spectrum corresponded to $\bar{\nu} = 2.9$. The resonance structure of the cross-sections was taken into account by the self-shielding factors.

(b) The results of calculations using the OSKAR-75 system are given in Ref. [7]. The OSKAR-75 system was obtained by fitting constants on the basis of the results of 48 integral experiments [8]. In the initial system of constants the values of σ_f and σ_c for ^{235}U, ^{238}U and ^{239}Pu correspond to the data from UKNDL, and the capture cross-section for Fe to the evaluation of the Nuclear Data Centre of the Institute of Physics and Power Engineering. The remaining cross-sections and the resonance self-shielding factors are assumed to be the same as in BNAB-70. The cross-sections σ_c, σ_f and ν for ^{235}U, ^{238}U and ^{239}Pu were fitted in three broad groups. Calculation of the standard reactor was performed with the 9M-26 program. The fission spectrum corresponded to $\bar{\nu} = 3.0$. Linear interpolation of the integral fluxes in the log-log scale was used to find the correction for the slowing-down cross-section.

(c) Calculations based on the BNAB-M system of constants. At the Institute of Physics and Power Engineering we have just completed a revision of nuclear data for ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{10}B, Fe, Ni and Cr, using the latest (up to beginning of 1977) data from the microscopic experiment. An experimental version of the BNAB-M constants has been compiled on the basis of these evaluations.*/ The data for O and Na in this version correspond to the BNAB-70 evaluations, and those for ^{241}Pu and ^{242}Pu to the preliminary evaluations. The results of the standard reactor calculation presented here were obtained by applying the ARAMAKO set of programmes [9]. A sub-group representation of cross-sections has been employed; the correction for the slowing-down cross-section was obtained in the Greuling-Goertzel approximation on the assumption that the cross-sections are constant in wide groups.

B. Cadarache, France [10]

The calculations were performed using the CARNAVAL-IV system [11] which was developed in 1976. Compared with the previous version, the constants for Fe, Ni, Cr and Na have been appreciably modified on the basis of the latest microscopic data and fitting to the integral experiment. The modifications to the constants of the higher isotopes of plutonium and the fission products have been harmonized with the results of measurements of fission rates in the MASURCA and ERMINE assemblies and of the reaction rates in irradiated samples in the Phenix and Rapsodie reactors. The authors of Ref. [11] consider that the CARNAVAL-IV system gives an error in the prediction of the criticality and the conversion ratio of a reactor rated at W ~ 1200 MW(e) in the mean steady state of ± 0.4% K_{eff} and ± 0.04 (absolute units).

C. Winfrith, England [12]

The calculations were performed with the FD-5 system of constants [13] which is being used for design calculations on the PFR and CFR reactors. As in the CARNAVAL system the role of integral data is considerable in the FD-5 system. The accuracy of prediction of the criticality and conversion rate for a large "clean" breeder is estimated as ± 0.5% K_{eff} and ± 0.03 (absolute units) [13].

D. Karlsruhe, FRG [14]

The KFKINR system of constants [15] developed in 1972 was used. The evaluations of the constants are based largely on microscopic

*/ A more complete version of these constants which is currently being compiled has been designated BNAB-MIKRO.

experiment data from the KEDAK library which have been corrected to harmonize them with the criticality of a set of uranium and plutonium assemblies. The error in the prediction of the criticality and the conversion ratio for the initial operating condition of the SNR reactor is evaluated in Ref. [16] as ± 0.8% K_{eff} and ± 6% (90% confidence limits) respectively. In our opinion the differences between the experimental and theoretical data for the large plutonium assembly, ZPR-6-7, presented in Ref. [7] confirm this evaluation: $K_{eff} = 0.997$, $c_8/f_9 = 0.152$, $f_2/f_9 = 0.0248$ (theor); $K_{eff} = 1.000 \pm 0.006$, $c_8/f_9 = 0.143 \pm 0.006$, $f_8/f_9 = 0.0239 \pm 0.011$ (experiment). The experimental values of the reaction rates have been reduced here to the conditions of the homogeneous calculation. The experimental error has increased in accordance with the considerations set forth in Ref. [4].

E. ANL, United States [18]

The ANL calculation was performed on the basis of ENDF/B-IV. The constants for the 26-group reactor calculation were prepared on the basis of MC^2-2 in the P1 approximation with $B^2_{core} = 9.34 \times 10^{-4}$ and $B^2_{refl.} = 0$. Results were obtained for variant A only. An idea of the reliability of such a calculation of plutonium systems may be obtained from the differences between the results of experiments on ZPR-6-7 (see Section D) and calculations: $K_{eff} = 0.984$, $c_8/f_9 = 0.156$, $f_8/f_9 = 0.0232$ [19].

3. Results of the comparison

Table 2 shows the nuclear concentrations corresponding to the critical state, the critical loadings of ^{239}Pu and ^{240}Pu and the equivalent critical loading (M_{equiv}). Table 3 shows the conversion characteristics. As the criticality of the system ($K_{eff} = 1.0102$) was not obtained in the ANL calculations, we introduced the corresponding corrections on the basis of calculations with the BNAB-M constants. The figures in brackets in Tables 2 and 3 are the initial ANL data. The following definitions were used in calculating the parameters given in Tables 2 and 3:

Equivalent critical mass

$$M_{equiv} = M_{49} + \omega_{40} M_{40} \cdot \frac{239{,}052}{240{,}054} \qquad (1)$$

Physical conversion ratio

$$B_{C \text{ or } S} = \frac{(C_{28} + C_{40})_{C \text{ or } S}}{(F_{49} + C_{49})_{C+S}} \qquad (2)$$

Breeding gain

$$G_{C \text{ or } S} = \frac{\left[C_{28} + C_{49}(\omega_{40} - 1) + C_{40}(\omega_{41} - \omega_{40}) - F_{49}\right]_{C \text{ or } S}}{\left[F_{28} + F_{49} + F_{40}\right]_{C+S}} \qquad (3)$$

"Equivalent weights" of isotopes

$$W_i = \frac{X_i - X_{28}}{X_{49} - X_{28}} \qquad X_i = \langle \nu\sigma_f \rangle - \langle \sigma_f \rangle - \langle \sigma_c \rangle \qquad (4)$$

The subscripts 28, 49, 40 and 41 relate to the isotopes ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu. The letters C and S indicate core and shield respectively.

Certain conclusions may be drawn on the basis of Tables 2 and 3.

(a) The critical loading of ^{239}Pu in the calculation with the BNAB-70 constants is greater than that in all the other calculations. The difference between the BNAB-70 calculation and the mean value is 37 kg (~ 2.1% K_{eff}) in variant A, and 31 kg (~ 1.8% K_{eff}) and 52 kg (~ 3.2% K_{eff}) in variants B and C. The increase in the discrepancy in variant C (large content of ^{240}Pu) is due largely to the 20-25% overstatement of the capture cross-section in ^{240}Pu in the BNAB-70 evaluations compared with the latest microscopic data. This is also the reason for the overstatement in the calculation with the OSKAR-75 system of the critical loading (~ 31 kg) for variant C, as the evaluations of the ^{240}Pu constants with OSKAR-75 correspond to the BNAB-70 data. This trend to overstatement of ^{240}Pu capture can be clearly traced both in the components of the neutron balance (Table 5) and in the average cross-sections over the core (Table 8).

(b) The critical loadings of ^{239}Pu in the calculations with OSKAR-75, CARNAVAL and KFKINR of variants A and B are similar (956, 946 and 945 kg for variant A, and 1025, 1020 and 1016 kg for variant B). As already mentioned, the KFKINR constants make a satisfactory prediction of the criticality of the ZPR-6-7 plutonium assembly, which is similar in composition to variant A of the standard reactor. Integral experiments on the ZPR-6-7 assembly were used in fitting the constants of the OSKAR-75 system [8]. As a result of fitting the criticality of the assembly was predicted to within 0.5% K_{eff}. Therefore it is not surprising to find that the OSKAR-75 and KFKINP calculations are in agreement. It can also be taken that the joint theoretical and experimental investigations performed on the SNEAK plutonium assemblies contributed to similar results being obtained in the calculations at Cadarache and Karlsruhe [20].

(c) The difference between the result of calculating the critical loading with the BNAB-M and ENDF/IV systems and the mean value of the KFKINR and CARNAVAL calculations is 27 kg (~ 1.4% K_{eff}) in all three variants, A, B and C. These figures are similar to the difference between calculation with BNAB-M and ENDF/B-IV and experiment for the conditions of the ZPR-6-7 assembly.

(d) The low critical loading in the calculation with FD-5 in variants A and B is noteworthy. The difference between this and the ENDF/B-IV and FD-5 calculations for example is 44 kg (~ 2.4% K_{eff}). However, in variant C with a high ^{240}Pu loading, the data for FD-5, CARNAVAL and KFKINR are similar. As follows from Table 6, this is due to the high ^{240}Pu capture cross-section in FD-5 compared with the above systems of constants.

(e) Table 3 shows that the variance of the breeding gain and the physical conversion ratio in the BNAB-M, CARNAVAL, KFKINR, FD-5 and ENDF/B-IV calculations is quite small at ~ $\pm$ 0.02, and that the relation $G \doteq (B-1) + 0.06$ holds. The overstatement of the conversion ratio in the BNAB-70 calculations, as was expected [4, 5], amounts to ~ 0.06. As follows from Table 3 the divergence is largely accounted for by the difference in the breeding in the core.

(f) In the fitting of the OSKAR-75 constants what we consider to be an unjustifiably high accuracy has been assumed for the reaction rates determining the neutron balance (in the first place c_8/f_9($\pm$ 2%), obtained in the experiment on the large plutonium assembly, ZPR-6-7. It has already been mentioned that the difference between experiment and calculation with the KFKINR, ENDF/B-IV and BNAB-M constants is 6-8%. There is also a direct indication of a possible systematic error in the experiment [21]. It is probable that this is one of the causes of the low conversion in the OSKAR-75 calculations.

Table 6 gives the neutron spectra of the core for variant A. Only the results of calculations performed in accordance with I.I. Bondarenko's energy grouping are presented. It will be noted that the deviation does not exceed ± 10% on average, i.e. is within the limits of accuracy of present-day experimental spectrometric methods. A slightly greater deviation occurs in the region of wide sodium resonance.

Table 7 shows the group shielded cross-sections for ^{239}Pu, ^{238}U and the values of ν. There is appreciable scatter for σ_f (^{239}Pu) (~ 15% in groups 14 and 15) and σ_c (^{238}U) (~ 25% in groups 14 and 16). The scatter in σ_c (^{239}Pu) is in our opinion lower than might be expected in view of the accuracy of the microscopic data.

We do not have any analogous data from France and the United Kingdom. Therefore it is useful to perform a comparison of the average cross-sections over the core which are easily obtainable from the neutron balance (Table 8). We have already mentioned that the calculations of integral neutron spectra in the core are similar. Therefore it may be expected that the deviation in the average cross-sections will be attributable mainly to the difference in the group constants. The validity of this assumption is confirmed by the figures in Table 9 which contains the results of averaging the BNAB-M group constants over different spectra from Table 6. On the basis of Table 8 it may be noted that:

(a) The average ^{238}U capture cross-section over the core in systems which have undergone fitting to integral data (OSKAR-75, CARNAVAL IV and FD-5) are ~ 6% lower than in the calculation with the BNAB-M, KFKINR and ENDF/B-IV systems which are based primarily on microscopic data;

(b) The value of α (^{239}Pu) in the OSKAR calculations is on average ~ 8% higher than in the other data;

(c) The scatter in the average capture cross-sections for Fe, Ni, Cr and Na reaches ~ 50%;

(d) The average cross-section for fission fragments in the CARNAVAL IV calculations differs appreciably from the other data. It may be noted that the figures given in Table 8 (0.496 for variant B and 0.489 for variant C) also differ appreciably from the analogous figures from the calculation with the previous version, CARNAVAL III [22] (0.522 and 0.519). These variations are mainly attributable to the variation in the fragment constants, since the neutron spectrum tended to become softer with the change-over from the third to the fourth version (see Table 10).

In Table 11 the results of calculation of the basic parameters of a standard reactor (variants A and C) presented in this paper are compared with the data obtained in 1970 [1]. It may be noted that:

(a) The critical loading in variant A has changed only little;

(b) The mean scatter in the conversion parameters ($\bar{B}$ = 1.32 ± 0.07 (1970); $\bar{B}$ = 1.31 ± 0.02 (1976), variant A) has decreased considerably. It does not of course follow from this that the real accuracy of the calculation of the physical conversion ratio is so high. In view of the correlation which undoubtedly exists between the basic nuclear data used in different laboratories one should rather consider the accuracy estimate of ± 0.02 as a lower one. It should also be noted that the considerable scatter in the critical loadings (973 kg for ENDF/B-IV and 929 kg for FD-5) in itself signifies an indeterminacy in the physical conversion ratio of ± 0.05;

(c) The mean scatter of data on the critical loading in variant C is still high today (M = 959 ± 18 in 1976 compared with M = 961 ± 20 in 1970).

<u>Conclusions</u>

On the basis of existing theoretical material the authors have come to the following conclusions:

(a) The growing convergence to be found in the results of calculations at different laboratories demonstrates objectively that the reliability of calculation of fast reactors in different countries has increased;

(b) There is still a significant indeterminacy in the prediction of one of the main physical characteristics - the critical loading.

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<u>Table 2</u>

Fuel concentration (10^{22} nucl/cm^3), critical mass and K_{eff}

		ρ (P_u-239)	ρ (P_u-240)	ρ (U-238)	M_{49} (кг)	M_{40} (кг)	Mequiv. (кг)	K_{eff}
Institute of Physics and Power Engineering (FEI) USSR BNAB-70	A	0,0999	0	0,620I	99I	0	99I	I,0005
	B	0,I060	0	0,5420	I052	0	I052	0,9988
	C	0,I0I0	0,0507	0,4960	I002	505	I036	0,998I
FEI, USSR OSKAR-75	A	0,0963	0	0,6237	956	0	956	0,9998
	B	0,I033	0	0,5447	I025	0	I025	I,0000
	C	0,0983	0,049I	0,5006	975	490	I008	0,9995
FEI, USSR BNAB-M	A	0,0975	0	0,6225	968	0	968	0,9996
	B	0,I054	0	0,5426	I046	0	I046	I,00I8
	C	0,0970	0,0485	0,5025	963	483	I038	I,00I0
Cadarache, France CARNAVAL IV	A	0,0957	0	0,6243	946	0	946	0,9992
	B	0,I026	0	0,5454	I0I8	0	I0I8	I,0008
	C	0,0956	0,0476	0,5043	948	476	I0I3	I,0008
Winfrith, UK FD-5	A	0,0936	0	0,6264	929	0	929	0,9996
	B	0,I004	0	0,5476	997	0	997	I,0003
	C	0,0938	0,0469	0,5073	93I	467	990	0,9998
Karlsruhe, FRG KFKINR	A	0,0952	0	0,6248	945	0	945	I,0000
	B	0,I024	0	0,5456	I0I6	0	I0I6	I,0000
	C	0,0940	0,0470	0,5070	933	468	I0I8	I,0000
ANL, USA ENDF/B-IV	A	0,0982	0	0,62I8	973	0	973	I,0000
		(0,0999)	0	(0,620I)	(99I)	0	(99I)	(I,0I02)

Note: The figures in brackets on the last line are the results supplied by ANL (calculation with K_{eff} = 1.01)

Table 3

Breeding characteristics

		$G_{A.3.}$	$G_{Э}$	G	$B_{A.3.}$	$B_{Э}$	B
Institute of Physics and Power Engineering (FEI) USSR BNAB-70	A	-0,I94	0,60I	0,407	0,764	0,609	I,373
	B	-0,327	0,587	0,260	0,643	0,589	I,232
	C	-0,065	0,570	0,505	0,766	0,623	I,389
FEI, USSR OSKAR-75	A	-0,296	0,547	0,25I	0,675	0,553	I,228
	B	-0,4I6	0,532	0,II6	0,566	0,534	I,I00
	C	-0,I56	0,52I	0,366	0,678	0,566	I,244
FEI, USSR BNAB-M	A	-0,224	0,576	0,352	0,7I6	0,580	I,296
	B	-0,36I	0,557	0,I96	0,593	0,557	I,I50
	C	-0,I83	0,552	0,369	0,705	0,604	I,309
Cadarache, France CARNAVAL IV	A	-0,238	0,6I3	0,375	0,702	0,6I0	I,3I2
	B	-0,368	0,594	0,226	0,587	0,586	I,I73
	C	-0,I99	0,587	0,389	0,686	0,629	I,3I6
Winfrith, UK FD-5	A	-0,229	0,598	0,369	0,707	0,6I3	I,320
	B	-0,358	0,576	0,2I8	0,593	0,582	I,I75
	C	-0,I76	0,567	0,39I	0,705	0,624	I,329
Karlsruhe, FRG KFKINR	A	-0,I95	0,584	0,390	0,730	0,588	I,3I9
	B	-0,329	0,566	0,237	0,6I0	0,566	I,I76
	C	-0,I96	0,563	0,366	0,70I	0,6I0	I,3II
ANL, USA ENDF/B-IV	A	-0,273 (-0,277)	0,568 (0,557)	0,295 (0,280)	0,7I3 (0,697)	0,567 (0,557)	I,280 (I,253)

Table 4

"Weights" of isotopes

		^{240}Pu	^{241}Pu	^{242}Pu	^{235}U
BNAB-70	A	0,027	-	-	-
	B	0,043	-	-	-
	C	0,067	I,79	-	-
OSKAR-75	A	0,026	-	-	-
	B	0,058	-	-	-
	C	0,067	I,74	-	-
BNAB-M	A	0,I47	I,53	-	0,8I9
	B	0,I37	I,50	-	0,79I
	C	0,I56	I,50	-	0,787
CARNAVAL IV	A	0,I04	I,55	0,0I2	0,789
	B	0,I22	I,52	0,024	0,777
	C	0,I37	I,52	0,028	0,773
FD-5	A	0,090	I,52	0,I08	-
	B	0,I07	I,49	0,I2I	-
	C	0,I26	I,48	0,I26	-
KFKINR	A	0,I60	I,49	0,044	0,804
	B	0,I76	I,46	0,059	0,788
	C	0,I83	I,46	0,059	0,788

Table 5-1

Neutron balance (FEI, BNAB-70)

	Nuclide	A			B			C		
		P	C	F	P	C	F	P	C	F
Core	^{239}Pu	804,65	79,04	273,93	822,65	76,I8	279,89	756,I9	67,85	257,I2
	^{240}Pu							77,00	5I,27	25,57
	^{238}U	I20,63	284,42	42,95	104,69	240,90	37,28	95,8I	2II,43	34,I2
	FP					56,58			52,94	
	Ni		3,2I			3,I5			3,08	
	Fe		8,4I			8,07			7,7I	
	Cr		2,66			2,54			2,42	
	Na		2,97			2,85			2,72	
	O		2,70			2,67			2,68	
Shield	^{239}Pu	38,27	6,08	I3,I7	36,95	5,78	I2,7I	35,75	5,54	I2,30
	^{238}U	36,45	226,54	I3,00	35,7I	220,53	I2,73	35,23	2I3,64	I2,57
	Ni		0,94			0,92			0,89	
	Fe		3,50			3,40			3,29	
	Cr		I,I5			I,I2			I,08	
	Na		0,87			0,84			0,82	
	O		0,68			0,67			0,66	
Sum		I000.00	623,I7	343,05	I000,00	626,20	342,6I	I000,00	628,02	34I,68
(n,2n)			0,00			0,00			0,00	
Leakage			33,48			32,69			32,40	
$(K_{eff}-1) \times 1000$			0,5			-I,2			-I,9	

Table 5-2

Neutron balance (FEI, OSKAR-75)

	Nuclide	A			B			C		
		P	C	F	P	C	F	P	C	F
Core	^{239}Pu	806,50	89,39	276,20	824,90	85,II	282,20	756,IO	75,28	258,50
	^{240}Pu							78,75	50,27	26,53
	^{238}U	II9,IO	260,80	43,3I	IO3,20	2I8,80	37,55	94,86	I92,50	34,50
	F.P.					57,4I			53,59	
	Ni		3,25			3,I7			3,IO	
	Fe		I3,3I			I2,55			II,87	
	Cr		2,73			2,57			2,44	
	Na		3,05			2,89			2,76	
	O		2,80			2,77				
Shield	^{239}Pu	40,00	6,95	I3,86	38,27	6,53	I3,25	37,I8	6,29	I2,87
	^{238}U	34,39	2I2,IO	I2,52	33,55	205,92	I2,22	33,I2	I99,60	I2,06
	Ni		0,97			0,94			0,92	
	Fe		6,04			5,83			5,84	
	Cr		I,23			I,I8			I,I5	
	Na		0,84			0,82			0,80	
	O		0,69			0,68			0,67	
Sum		I000,00	604,15	345,89	999,92	607,I7	345,22	I000,0I	607,08	344,46
(n,2n)			0,00			0,00			0,00	
Leakage			49,95			43,13			45,82	
$(K_{eff}-1) \times 1000$			-0,2			0,0			-0,5	

Table 5-3

Neutron balance (FEI, BNAB-M)

	Nuclide	A P	A C	A F	B P	B C	B F	C P	C C	C F
Core	^{239}Pu	803,77	84,4I	275,3I	823,I9	80,2I	28I,8I	745,32	7I,87	254,99
	^{240}Pu							86,26	37,93	27,52
	^{238}U	II9,88	272,57	43,33	I03,34	226,29	37,36	95,93	206,40	34,69
	F.P.					59,55			57,8I	
	Ni		4,05			3,93			3,89	
	Fe		II,56			I0,94			I0,72	
	Cr		4,93			4,63			4,53	
	Na		3,22			3,0I			2,95	
	O		2,68			2,63			2,64	
Shield	^{239}Pu	35,73	6,84	I4,07	38,7I	6,42	I3,4I	38,02	6,29	I3,I6
	^{238}U	40,62	220,76	I2,92	34,76	2I2,79	I2,56	34,47	209,26	I2,46
	Ni		I,32			I,28			I,26	
	Fe		5,02			4,84			4,76	
	Cr		2,22			2,I4			2,II	
	Na		0,96			0,92			0,90	
	O		0,69			0,67			0,67	
	Sum	I000,00	62I,73	345,63	I000,00	620,25	345,I4	I000,00	623,99	342,82
	(n,2n)		0,00			0,00			0,00	
	Leakage		32,64			34,6I			33,I9	
	$(K_{eff}-1) \times 1000$		-0,40			I,80			I,00	

Table 5-4

Neutron balance (CARNAVAL IV)

	Nuclide	A			B			C		
		P	C	Γ	P	C	Γ	P	C	Γ
Core	^{239}Pu	794,927	86,625	27I,933	8I2,842	84,04I	277,828	743,597	76,03I	254,076
	^{240}Pu	-	-	-	-	-	-	78,046	36,295	25,072
	^{238}U	I2I,6I0	267,876	42,392	I06,I59	225,28I	37,009	98,443	205,280	34,320
	FP	-	-	-	-	53,924	-	-	52,345	-
	Ni	-	3,599	-	-	3,5I4	-	-	3,479	-
	Fe	-	9,405	-	-	8,843	-	-	8,634	-
	Cr	-	2,76I	-	-	2,60I	-	-	2,540	-
	Na	-	2,96I	-	-	2,72I	-	-	2,640	-
	O	-	2,034	-	-	2,029	-	-	2,034	-
Shield	^{239}Pu	44,994	7,478	I5,563	43,269	7,I22	I4,964	42,489	6,975	I4,693
	^{238}U	38,470	232,674	I3,448	37,729	225,II4	I3,I90	37,425	22I,255	I3,084
	Ni	-	I,23I	-	-	I,I97	-	-	I,I80	-
	Fe	-	4,698	-	-	4,528	-	-	4,445	-
	Cr	-	I,405	-	-	I,358	-	-	I,334	-
	Na	-	I,I40	-	-	I,098	-	-	I,077	-
		-	0,5II	-	-	0,500	-	-	0,496	-
Sum		I,000	624,398	343,336	I,000	623,87I	342,99I	I,000	626,040	34I,245
Leakage			32,266			33,I38			32,7I5	
$(K_{eff}-1) \times 1000$			-0,794			0,820			0,800	

Table 5-5

Neutron balance (FD-5)

	Nuclide	A			B			C		
		P	C	Γ	P	C	Γ	H	C	Γ
Core	^{239}Pu	788,85	80,89	268,I8	8I0,64	78,60	275,4I	739,59	70,58	25I,I9
	^{240}Pu	-	-	-				80,64	39,87	25,54
	^{238}U	I26,55	262,98	45,69	I08,67	222,68	39,24	I00,52	20I,94	36,29
	FP	-	-	-		55,24			53,I6	
	Ni		3,46			3,36			3,3I	
	Fe		I4,54			I3,75			I3,32	
	Cr		2,30			2,I8			2,I2	
	Na		2,63			2,48			2,4I	
	O		I,73			I,7I			I,7I	
Shield	^{239}Pu	45,29	7,39	I5,57	43,I5	6,97	I4,84	42,I6	6,79	I4,50
	^{238}U	39,3I	227,88	I4,2I	37,54	2I8,59	I3,57	37,09	2I3,90	I3,4I
	Ni		I,24			I,20			I,I7	
	Fe		6,66			6,38			6,23	
	Cr		I,I5			I,I0			I,08	
	Na		0,75			0,72			0,70	
	O		0,44			0,42			0,4I	
	Sum	I000,00	6I4,04	343,65	I000,00	6I5,38	343,06	I000,00	6I8,70	340,93
	(n, 2n)		I,90			I,70			I,64	
	Leakage		44,66			42,97			42,2I	
	$(K_{eff}-1) \times 1000$		-0,45			0,29			-0,I9	

Table 5-6

Neutron balance (KFKINR)

	Nuclide	A P	A C	A F	B P	B C	B F	C P	C C	C F
Core	^{239}Pu	800,92	8I,I8	272,I9	8I9,79	77,38	278,38	749,49	70,80	253,84
	^{240}Pu	-	-	-				80,92	28,09	25,73
	^{238}U	II8,50	273,74	42,I3	I02,43	229,48	36,43	94,84	2I3,65	33,72
	FP	-	-	-		59,I2			58,62	
	Ni		3,78			3,66			3,65	
	Fe		I8,I4			I7,II			I7,06	
	Cr		2,5I			2,37			2,35	
	Na		2,8I			2,60			2,59	
	O		I,6I			I,58			I,58	
Shield	^{239}Pu	42,52	6,82	I4,60	40,72	6,43	I3,98	40,I7	6,35	I3,79
	^{238}U	38,03	220,49	I3,52	37.04	2I2,99	I3,I7	36,57	2I0,36	I3,00
	Ni		I,33			I,29			I,28	
	Fe		8,24			7,96			7,86	
	Cr		I,I7			I,I3			I,II	
	Na		0,86			0,82			0,8I	
	O		0,44			0,43			0,43	
Sum		I000,00	623,I3	342,46	I000,00	624,35	34I,97	I000,00	626,6I	340,09
(n, 2n)			2,06			I,86			I,79	
Leakage			36,47			35,6I			35,II	
$(K_{eff}-1) \times 1000$			0,002			-0,062			-0,0I2	

Table 5-7

Neutron balance (ANL, ENDF/B-IV)

Nuclide	A		
	P	C	F
^{239}Pu	811,70	84,93	279,76
^{240}Pu			
^{238}U	116,02	268,50	42,33
Ni		4,30	
Fe		14,44	
Cr		5,66	
Na		4,03	
O		2,20	
^{239}Pu	39,24	6,73	13,69
^{238}U	33,04	214,07	12,08
Ni		1,42	
Fe		6,18	
Cr		2,48	
Na		1,16	
O		0,51	
Sum	1000,00	616,61	347,86
(n, 2n)	-	-	-
Leakage		25,46	
$(K_{eff}-1) \times 1000$		10,2	

Table 6

Neutron spectra in the core, variant A

No. of Groups	E	I	2	3	4	5
I	I0,5-6,5 MeV	0,00I8	0,00I8	0,00I7	0,0022	0,00I9
2	6,5-4,5	0,0I02	0,0I03	0,0099	0,0I03	0,0I04
3	4,5-2,5	0,0243	0,0242	0,0256	0,0240	0,0243
4	2,5-I,4	0,0499	0,0500	0,0483	0,0496	0,0482
5	I,4-0,8	0,0599	0,060I	0,060I	0,0594	0,06I2
6	0,8-0,4	0,I283	0,II32	0,II46	0,I202	0,II73
7	0,4-0,2	0,I385	0,I498	0,I433	0,I392	0,I424
8	0,2-0,I	0,I580	0,I537	0,I6II	0,I535	0,I60I
9	I00-46,5 keV	0,I455	0,I380	0,I393	0,I405	0,I479
I0	46,5-2I,5	0,IIII	0,III5	0,II45	0,II30	0,I099
II	2I,5-I0	0,0803	0,0825	0,079I	0,0854	0,08I0
I2	I0-4,65	0,048I	0,0442	0,0426	0,0442	0,0490
I3	4,65-2,I5	0,009I	0,0II2	0,0I29	0,0I23	0,009I
I4	2,I5-I	0,0I82	0,0288	0,0266	0,0262	0,0I98
I5	I000-465 eV	0,0II5	0,0I45	0,0I47	0,0I37	0,0I2I
I6	465-2I5	0,004I	0,0048	0,0044	0,0049	0,0042
I7	2I5-I00	0,00093	0,00I2	0,00II	0,00II	0,00092
I8	I00-46,5	0,000I0	0,000I7	0,000I3	0,000I6	0,000I3
I9	46,5-2I,5	0,0^{4}I0	0,0^{4}2I	0,0^{4}I9	0,0^{4}I5	0,0^{4}I8
20	2I,5-I0	0,0^{5}I	0,0^{5}2	0,0^{5}I	0,0^{5}I	0,0^{5}I

Note: (1) BNAB-70; (2) BNAB-M; (3) KFKINR; (4) ENDF/BIV; (5) OSKAR-75

Table 7

Self-Shielded group cross-sections of the core, variant A

No. of group	ν (^{239}Pu)				σ_f (^{239}Pu)				σ_c (^{239}Pu)				σ_c (^{238}U)			
	I	2	3	4	I	2	3	4	I	2	3	4	I	2	3	4
I	3,86	4,03	4,09	4,0I	2,2I	2,23	2,09	2,22	0,0I	$0,0^{2}44$	$0,0^{2}I0$	$0,0^{3}60$	$0,0^{2}60$	$0,0^{2}56$	$0,0^{2}50$	$0,0^{2}36$
2	3,5I	3,63	3,62	3,59	I,72	I,79	I,72	I,73	0,02	$0,0^{2}66$	$0,0^{2}23$	$0,0^{2}I5$	0,0I2	0,0II	$0,0^{2}90$	$0,0^{2}92$
3	3,27	3,33	3,32	3,32	3,32	I,86	I,87	I,85	0,03	0,0II	$0,0^{2}50$	$0,0^{2}32$	0,024	0,02I	0,02I	0,024
4	3,I2	3,I4	3,I4	3,I4	I,97	I,93	I,95	I,93	0,04	0,022	0,0II	$0,0^{2}94$	0,060	0,049	0,055	0,059
5	3,0I	3,0I	3,03	3,02	I,76	I,78	I,74	I,75	0,04	0,052	0,022	0,025	0,I3	0,II	0,I3	0,II
6	2,95	2,93	2,96	2,95	I,59	I,65	I,6I	I,6I	0,I0	0,II2	0,065	0,09I	0,I3	0,I2	0,I3	0,II
7	2,9I	2,89	2,92	2,9I	I,53	I,5I	I,55	I,5I	0,I6	0,I54	0,I6	0,I8	0,I4	0,I3	0,I3	0,I2
8	2,89	2,88	2,9I	2,89	I,50	I,50	I,53	I,53	0,23	0,20	0,22	0,22	0,I8	0,I6	0,I8	0,I6
9	2,88	2,87	2,90	2,88	I,47	I,6I	I,58	I,60	0,26	0,30	0,25	0,35	0,26	0,26	0,28	0,26
I0	2,87	2,87	2,89	2,87	I,59	I,6I	I,69	I,62	0,48	0,49	0,5I	0,50	0,44	0,45	0,44	0,4I
II	2,87	2,86	2,89	2,87	I,74	I,74	I,84	I,74	0,83	0,84	0,83	0,86	0,62	0,6I	0,54	0,55
I2	2,87	2,86	2,89	2,87	2,I6	2,I2	2,3I	2,08	I,67	I,5I	I,60	I,46	0,80	0,78	0,70	0,72
I3	2,87	2,86	2,89	2,87	2,88	2,99	3,25	2,73	2,88	2,70	2,93	2,49	I,I4	0,98	I,09	0,95
I4	2,87	2,86	2,89	2,87	4,0I	4,04	4,44	4,26	3,72	3,58	3,97	3,50	I,I2	0,78	0,9I	0,98
I5	2,87	2,86	2,89	2,87	6,85	7,44	6,49	6,78	5,28	5,8I	5,5I	5,36	I,07	0,96	0,92	I,09
I6	2,87	2,86	2,89	2,87	I0,7	I0,4	I0,6	9,59	8,52	8,82	8,I0	8,00	I,22	I,I4	0,95	I,I2
I7	2,87	2,86	2,89	2,87	I5,8	I3,0	I4,I	I4,6	I2,8	9,63	9,I9	I0,2	2,04	I,78	I,60	I,67
I8	2,87	2,86	2,89	2,87	38,7	38,5	39,7	38,3	3I,2	I7,9	I6,2	I5,8	I,79	I,56	I,62	I,35
I9	2,87	2,86	2,89	2,87	I4,8	I3,5	8,72	6,22	2I,I	I2,9	I5,6	20,4	3,32	3,26	3,22	3,90
20	2,87	2,86	2,89	2,87	70,2	53,4	4I,4	26,8	42,8	29,9	28,2	I6,I	4,50	3,39	5,73	20,8

Note: (1) BNAB-70; (2) BNAB-M; (3) KFKINR; (4) ENDF/BIV

Table 8

Average cross-sections over the core

	FEI, USSR BNAB-70			FEI, USSR OSKAR-75			FEI, USSR BNAB-M		
	$\langle \nu\sigma_f \rangle$	$\langle \sigma_c \rangle$	$\langle \sigma_f \rangle$	$\langle \nu\sigma_f \rangle$	$\langle \sigma_c \rangle$	$\langle \sigma_f \rangle$	$\langle \nu\sigma_f \rangle$	$\langle \sigma_c \rangle$	$\langle \sigma_f \rangle$
				Variant A					
^{239}Pu	5,28I	0,5I9	I,798	5,423	0,60I	I,857	5,499	0,577	I,883
^{240}Pu	-	0,809	0,337	I,060	0,824	0,358	I,220	0,668	0,390
^{238}U	0,1275	0,30I	0,0454	0,I24	0,27I	0,0450	0,I285	0,292	0,0464
F.P		-			0,577			-	
Ni		0,0239			0,0239			0,0307	
Fe		0,0068			0,0I06			0,0095	
Cr		0,0088			0,0089			0,0I66	
Na		0,00I6			0,00I6			0,00I7	
O		0,00I2			0,00I3			0,00I2	
				Variant B					
^{239}Pu	5,I70	0,479	I,759	5,285	0,545	I,808	5,339	0,520	I,828
^{240}Pu	-	0,759	0,339	I,072	0,765	0,362	I,229	0,60I	0,393
^{238}U	0,I287	0,296	0,0458	0,I25I	0,266	0,0456	0,I302	0,285	0,047I
F.P		0,524			0,528			0,565	
Ni		0,0238			0,0238			0,0305	
Fe		0,0066			0,0I02			0,0092	
Cr		0,0086			0,0086			0,0I60	
Na		0,00I5			0,00I6			0,00I7	
O		0,00I2			0,00I3			0,00I3	
				Variant C					
^{239}Pu	5,I35	0,46I	I,746	5,242	0,522	I,792	5,325	0,5I3	I,822
^{240}Pu	I,04I	0,694	0,346	I,093	0,697	0,368	I,232	0,542	0,393
^{238}U	I,325	0,292	0,0472	0,I290	0,262	0,0469	0,I323	0,285	0,0478
F.P		0,504			0,507			0,556	
Ni		0,0240			0,0240			0,0306	
Fe		0,0065			0,0099			0,009I	
Cr		0,0084			0,0084			0,0I59	
Na		0,00I5			0,00I5			0,00I7	
O		0,00I3			0,00I3			0,00I3	

Table 8 (continued)

	Cadarache, France CARNAVAL IV			Winfrith, UK FD-5		
	$\langle\nu\sigma_f\rangle$	$\langle\sigma_c\rangle$	$\langle\sigma_f\rangle$	$\langle\nu\sigma_f\rangle$	$\langle\sigma_c\rangle$	$\langle\sigma_f\rangle$
			Variant A			
^{239}Pu	5,388	0,587	I,843	5,50I	0,564	I,870
^{240}Pu	-	-	-	-	-	-
^{238}U	0,I263	0,278	0,0440	0,I32	0,274	0,0477
F.P	-	-	-	-	-	-
Ni		0,0265			0,0256	
Fe		0,0075			0,0II6	
Cr		0,0090			0,0077	
Na		0,00I6			0,00I4	
O		0,00092			0,00079	
			Variant B			
^{239}Pu	5,252	0,543	I,795	5,375	0,520	I,826
^{240}Pu	-	-	-	-	-	-
^{238}U	0,I290	0,274	0,0450	0,I32	0,27I	0,0477
F.P.		0,496			0,5II	
Ni		0,0265			0,0254	
Fe		0,0072			0,0II3	
Cr		0,0087			0,0073	
Na		0,00I5			0,00I4	
O		0,00093			0,00079	
			Variant C			
^{239}Pu	5,233	0,535	I,788	5,350	0,5II	I,8I7
^{240}Pu	I,098	0,5II	0,353	I,167	0,576	0,369
^{238}U	0,I3I3	0,274	0,0458	0,I34	0,270	0,0485
F.P		0,489			0,50I	
Ni		0,0266			0,0256	
Fe		0,007I			0,0III	
Cr		0,0086			0,0073	
Na		0,00I4			0,00I3	
O		0,00095			0,00080	

Table 8 (continued)

	Karlsruhe, FRG KFKINR			ANL, USA ENDF/BIV		
	$\langle \nu\sigma_f \rangle$	$\langle \sigma_c \rangle$	$\langle \sigma_f \rangle$	$\langle \nu\sigma_f \rangle$	$\langle \sigma_c \rangle$	$\langle \sigma_f \rangle$
			Variant A			
^{239}Pu	5,593	0,567	I,90I	5,454	0,566	I,864
^{240}Pu	-	-	-	-	-	-
^{238}U	0,I26I	0,29I	0,0448	0,I233	0,283	0,0445
FP		-			-	
Ni		0,0285			0,0320	
Fe		0,0I48			0,0II6	
Cr		0,0084			0,0I87	
Na		0,00I5			0,002I	
O		0,00074			0,00I0	
			Variant B			
^{239}Pu	5,45I	0,5I45	I,85I	(Results not supplied)		
^{240}Pu	-	-	-			
^{238}U	0,I278	0,2864	0,0455			
F.P		0,559				
Ni		0,0283				
Fe		0,0I43				
Cr		0,0082				
Na		0,00I4				
O		0,00075				
			Variant C			
^{239}Pu	5,45I	0,5I6	I,85I	(Results not supplied)		
^{240}Pu	I,I80	0,4I0	0,375			
^{238}U	0,I282	0,289	0,0456			
FP		0,558				
Ni		0,0284				
Fe		0,0I44				
Cr		0,008I				
Na		0,00I4				
O		0,00075				

Table 9

Averaging of BNAB-M constants over different spectra

Cross-section	Averaged spectrum			
	BNAB-70	BNAB-M	KFKINR	ENDF/BIV
σ_f (^{239}Pu)	I,828	I,884	I,874	I,875
σ_c (^{239}Pu)	0,5I35	0,578I	0,5680	0,5700
σ_c (^{238}U)	0,2833	0,2935	0,29I8	0,2940

Table 10

Neutron spectrum of the core on the basis of CARNAVAL III and CARNAVAL IV Variant C

Groups	Energy range		CARNAVAL III	CARNAVAL IV
I	I4,5-3,68	MeV	0,0I46	0,0I42
2	3,68-2,23		0,0324	0,0325
3	2,23-I,35		0,046I	0,0458
4	I,35-0,82I		0,0583	0,0595
5	82I-498	keV	0,0974	0,0994
6	498-302		0,0855	0,0833
7	302-I83		0,II23	0,III2
8	I83-III		0,II55	0,II36
9	III-67,4		0,0976	0,099I
I0	67,4-40,9		0,0829	0,0825
II	40,9-24,8		0,0672	0,0708
I2	24,8-I5		0,0630	0,062I
I3	I5-9,I2		0,0447	0,0459
I4	9,I2-5,53		0,0267	0,0274
I5	5,53-3,36		0,0I45	0,0I45
I6	3,36-2,04		0,0I05	0,0052
I7	2,04-I,23		0,0I60	0,0I59
I8	I,23-0,748		0,0085	0,0098
I9	748-454	eV	0,0039	0,0044
20	454-275		0,00I6	0,00I9
2I	275-I0I		$0,0^{3}65$	$0,0^{3}78$
22	I0I-22,6		$0,0^{4}48$	$0,0^{4}60$
23	22,6-3,06		$0,0^{5}I3$	$0,0^{6}84$
24	3,06-0,4I4		$0,0^{7}40$	$0,0^{8}65$

Table 11

Comparison of calculations of standard reactors in 1970 and 1976

	FEI		CADARACHE		WINFRITH		KARLSRUHE		ANL	
	1970	1976	1970	1976	1970	1976	1970	1976	1970	1976
$M(^{239}Pu)$ [kg]	975	968	952	946	939	929	96I	945	978	973
B	I,34	I,30	I,25	I,3I	I,26	I,32	I,3I	I,32	I,4I	I,28
B_{core}	0,74	0,72	0,67	0,70	0,69	0,7I	0,74	0,73	0,79	0,7I
G	0,37	0,35	0,30	0,38	0,34	0,37	0,38	0,39	0,46	0,30
c_8/f_9	0,I6I	0,I55	0,I47	0,I5I	0,I46	0,I47	0,I60	0,I53	0,I64	0,I52
α_9	0,30I	0,306	0,334	0,3I9	0,306	0,302	0,3I2	0,298	0,253	0,304
f_8/f_9	0,0247	0,0246	0,0224	0,0239	0,022I	0,0255	0,0226	0,0236	0,0239	0,0239
f_9	I,82	I,83	I,89	I,84	I,92	I,87	I,87	I,90	I,89	I,86
$M(^{239}Pu)$ [kg]	I006	963	956	948	929	990	965	933	95I	-
B	I,36	I,3I	I,26	I,3I	I,25	I,33	I,28	I,3I	I,42	-
B_{core}	0,74	0,7I	0,67	0,68	0,66	0,7I	0,70	0,70	0,75	-
G	0,44	0,37	0,39	0,38	0,3I	0,39	0,36	0,37	0,46	-
c_8/f_9	0,I62	0,I56	0,I49	0,I53	0,I48	0,I49	0,I62	0,I56	0,I62	-
α_9	0,270	0,282	0,3I0	0,299	0,28I	0,282	0,290	0,279	0,237	
c_{40}/f_9	0,4I4	0,298	0,3I6	0,286	0.I98	0,3I7	0.240	0,222	0,238	-
f_8/f_9	0,0268	0,0262	0,0236	0,0256	0,0236	0,0267	0,0242	0,0246	0,0264	-
f_9	I,75	I,82	I,83	I,79	I,83	I,82	I,8I	I,85	I,84	-