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SELF-SHIELDING FACTORS OF ^{240}Pu FOR THE HEAVY WATER FUEL CELL OF THE BLANKET OF ELECTRONUCLEAR FACILITY

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The method for calculation of Pu-240 self-shielding factors for the heavy water fuel cell of the blanket of electronuclear facility for long-living radioactive waste transmutation are presented and these results of computing are analyzed. Variants of simplification for the cell geometry are considered. The correctness of considered approaches is confirmed by results of the calculation. The modeling of neutrons transport is carried out under the reactor MCU-code (Monte Carlo method).

Fig. - 16, ref. - 6 name.

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The self-shielding of resonances can considerably (or strongly in number of cases) reduce a rate of corresponding reactions in a resonance interval of energy. Self-shielding factors [1] are the measure of change for a resonance interaction rate at a resonance self-shielding. The given work is concerned with determination of capture self-shielding factors for the Pu-240 isotope and is performed within development of the project for transmutation of radioactive nuclides. The absence of these data for dilution cross sections $\sigma_0 > 10^4$ b and presence of a heterogeneous medium (where a transmutation occurs) have caused necessity of these calculations.

The isotope Pu-240 has the large resonance capture integral $I_{n\gamma}$ = 8475.0 b, fission resonance integral is small - I_{nf} = 9.369 b [2,3]. The main contribution to the value of $I_{n\gamma}$ gives the first resonance with the average energy E_r = 1.056 eV [4], i.e. at the bound of 23-rd and 24-th neutron groups of the 28-neutron-group structure BNAB [1,5].

The given method of calculation for resonance self-shielding factors is based on that at the small concentrations C_1, C_2, C_3 (where $C_3 > C_2 > C_1$) of a researched resonance nuclide the rates of the resonance reaction R_1^k, R_2^k, R_3^k (where k - is the neutron group) is directly proportional to the concentration of this nuclide $R_3^k : R_2^k : R_1^k = C_3 : C_2 : C_1$,

i.e $R_2^k C_1 / R_1^k C_2 = 1$ and $R_3^k C_1 / R_1^k C_3 = 1$.

With increase of concentration of the nuclide (let us at the concentration C_4) the effect of cross sections self-shielding begins display and the linear dependence is disturbed: $R_4^k : R_1^k < C_4 : C_1$, i.e. $R_4^k C_1 / R_1^k C_4 < 1$

The value

$$f^k = R_i^k C_1 / R_1^k C_i$$

is the required self-shielding factor for this cross section in the group k at the concentration C_i of the cosidered resonance nuclide.

Thus for Pu-240 the dependences of capture resonance self-shielding factors on concentration Pu-240 were determined for different neutron groups. These dependences are obtained for infinite lattice formed from hexahedral cells in a real and simplified geometries (ring-shaped geometry and homogenizated one).

The cell in the real geometry is presented in fig. 1. The zones are separated by zirconium tubes. A heavy water solution of isotopes Pu-239 and Pu-240 (zone 1 and 11) is the fuel. In a functioning facility it is provided circulation of the fuel between the central tube (zone 1) and thin fuel tubes (zone 11). In the zones 3 and 5 the heavy water is pumped under the pressure of 100 atmospheres and is a heat-carrier. The heavy water in the intercell space (zone 9) is a moderator functionally.

Modeling performed for the cell in the real geometry is compared below with results for the ring-shaped (marked as 'rings' geometry on figures below) and homogenizated geometry. At modification of the real geometry into ring-shaped (fig. 2) the three layers of thin fuel tubes in the real geometry are transformed into the three cylindrical fuel layers with

conservation of the radius for the middle of the layer. I.e., the three values of radiuses r = 5.0, 6.3 and 7.6 cm (see Fig. 1) at transition into the ring-shaped geometry were not changed. The thickness of three fuel layers and them zirconium jackets (fig. 2) are designed from the requirement: nuclear concentration must remain invariant. I.e., the isotope concentrations in the zones 3, 10 and 11 of the ring-shaped geometry are equal to the concentrations for the zones 3, 10 and 11 of the real geometry.

The further simplification of the design-basis geometry consists in homogenization for the zones 1, 2, 3, 10 and 11 of the real geometry. The geometry of the homogenizated cell is presented in fig. 3.

The modeling of the neutron field is executed under the reactor code MCU verificated in calculations about 300 experimental assemblies [6]. The height of cells is assumed equal 4 m. In calculations it was set mirror reflection on bounds of cells and absorption at end faces. In the task specification for MCU the temperature of cells is determined equal 300°K.

At the first stage of work the Pu-240 isotope was excluded from the compozition of the fuel in the real geometry and the concentration of Pu-239 was brought up to the value 6.564 E-6 (here and further the nuclear concentration is given in units - 10^{24} nuclei/cm^3) that provided $k_\infty = 1$. Further the concentration of Pu-239 remained constant in the all calculations and the concentration of Pu-240 varied only. The modeling was performed at the next relative concentration: x = (concentration of Pu-240) / (concentration of Pu-239) = 0.00025, 0.0025, 0.025, 0.05, 0.1, 0.2, 0.3, 0.5 specified on the all figures. The first point - x = 0.00025 is used for normalization of the reaction rates and, therefore, it is absent in the figures. Nuclear concentration of the zones for the real, ring-shaped and homogenizated geometries are given in the tables 1 and 2 of the appendix where for the value "x" appropriate concentrations of Pu-240

are specified.

The self-shielding factors f_c of Pu-240 in the zone 11 (thin fuel tubes) are presented in fig. 4 for the groups 21÷26.The self-shielding is displayed maximally in the group 23, in a smaller degree -in the group 24 and it is expressed very slightly in the group 22. These groups 22÷24 are the groups in which the powerful resonance (with E_r = 1.056 eV) presents. In the group 21 the action of this resonance is not displayed, i.e. the value f_c is practically equal to unity. In the intervals of 25-th and 26-th energy groups this resonance is also absent.However, the strong neutrons absorption in the 23-rd and 24-th groups results in significant decrease of neutrons number scattered into 25-th and 26-th groups. It causes decrease of absorption rate in the 25-th and 26-th groups. In groups where resonances are not present (group 21, 25, 26) it is more properly to tell about calculation of a functional f_c, instead of a self-shielding factor. Therefore, the some figures for these groups are denoted just as the functional f_c.

Self-shielding factors (with statistical errors) for the groups 21÷26 in the real, ring-shaped and homogenizated geometry are presented in fig. 5-10. For clearness the error bars for the ring-shaped geometry are inclined left and in homogenizated geometry - right to the vertical. Results for the real and ring-shaped geometry are close and the error bars are overlaped. Values of factors in the homogenizated geometry, as a rule, more than in the real one.The maximum distinctions are exist in the 23-rd group where at x =0.2, 0.3 and 0.5 the error intervals in the real and the homogenizated geometries are not overlaped. Such distinctions confirm the expected physical effect: decreasing of the self-shielding at homogenization of Pu-240.

Intervals of errors and fited curves (by exponential curves $y = A\ exp(Bx)$) of Pu-240 self-shielding factors are presented in fig. 11 for the groups 17÷21.The 21-st group values does not practically differ from unity and

it confirms the correctness of the fit. The maximum self-shielding is displayed in the 19-th group. The smaller self-shielding (with respect to decrease) - is displayed in the groups 18, 17, 20. Such behaviour of the self-shielding factors corresponds roughly to the group cross sections of absorption [5]: 67.65 b (group 19), 42.29 b (group18), 27.000 b (group 17), 30.71 b (group 20), 0.78 b (group 21). The given figure is presented for demonstration of the tendencies in behaviour of f_c factors (but not the value of f_c) in these groups. In order to obtain the values of f_c factors the statistics must be increased considerably.

The considered above self-shielding factors are presented for the zone of the thin fuel tubes (zone 11). It is necessary to compare these self-shielding values of Pu-240 with the values of the self-shielding in a more voluminous central fuel tubes (zone 1) where greater effect of the self-shielding is expected. In a tube of a bigger diameter the large part of volume (in comparison with thin fuel tubes) is shielded from resonances. Really, the calculations (see fig. 12÷16) give considerably smaller f_c -factors for the central tube - zone 1. In the group 22 (where the self-shielding is small) and group 26 (where the effect from neutron absorption in the first resonance is considerably reduced) the f_c -values in the zones 1 and 11 approach.

The value of self-shielding factors are obtained at dilution cross sections σ_o are well large than in the Ref [5]. The dilution cross sections at x = 1.0 in the real, ring-shaped and homogenizated geometry for groups 22÷24 (Pu-239 has not resonances in these groups) are presented in table 1. In order to obtain dilution cross sections for the next relative concentration of Pu-240 x = 0.0025, 0.025, 0.05, 0.1, 0.2, 0.3, 0.5 it is necessary the values in the table to divide into appropriate values of "x".

Table 1

Neutron Group	Cross section of Dilution (barn) for Real, Ring-shaped and Homogenizated Geometry (zone 1)	Cross section of Dilution (barn) for Homogenizated Geometry (zone 3)
22	43252	86331
23	43268	86347
24	43384	86464

The results presented in figures are obtained at statistics given in the table 2 where the concentrations of Pu-240 are specified as x-value (i.e. as in the figures)

Table 2

concentration of Pu-240	**Number of Histories for the Cell Geometries**		
	Real	Ring-shaped	Homogenizated
x = 0.0025	963000	720000	-
x = 0.025	1656000	744000	-
x = 0.05	1998000	876000	720000
x = 0.1	1953000	720000	720000
x = 0.2	1350000	732000	720000
x = 0.3	2241000	720000	720000
x = 0.5	1512000	900000	720000

The values k_∞ (according to Brissenden evaluation - k_{Bris}) obtained for these geometries are presented in table 3 where errors are specified in brackets (i.e., for example the value 1.0031(5) means 1.0031±0.0005). The closeness of values k_{Bris} in the ring-shaped and homogenizated geometry to the values in the real geometry confirms correctness of simplifications for this

lattice geometry.

Table 3

concentration of Pu-240	Comparison of k_∞ – values for the Cell in the Real, Ring-shaped and Homogenizated Geometry		
	Real	Ring-shaped	Homogenizated
x = 0.0025	1.0031(5)	1.0036(6)	-
x = 0.025	0.99851(36)	0.99719(63)	-
x = 0.05	0.99230(33)	0.99162(56)	0.99191(61)
x = 0.1	0.98126(33)	0.97913(65)	0.98159(57)
x = 0.2	0.96084(42)	0.96007(62)	0.96013(63)
x = 0.3	0.94273(29)	0.94228(61)	0.94146(59)
x = 0.5	0.90739(37)	0.90781(56)	0.90680(62)

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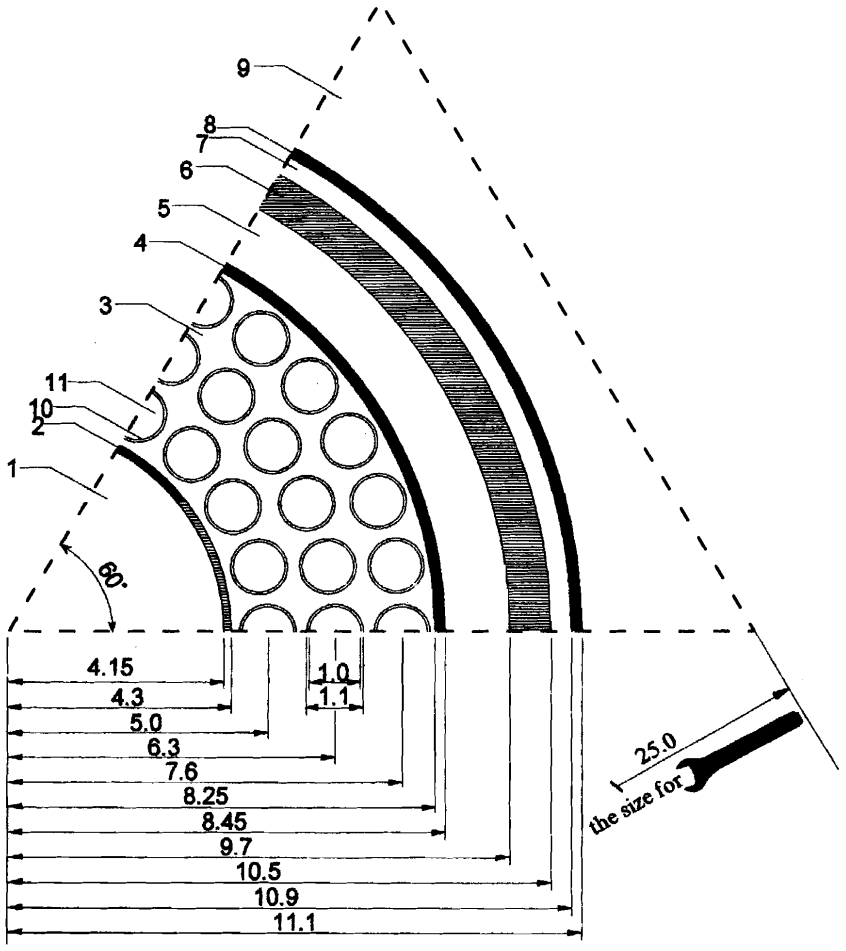

Fig. 1. Geometry of the cell (dimensions in cm). 1 - liquid fuel; 2 - central tube for liquid fuel; 3 - moderator (D_2O), zone of heat releasing; 4 - tube separated flows of heat transport heavy water; 5 - cooled volume of heat transport heavy water (zone of heat removal); 6 - load-bearing tube; 7 - heat-insulated gap; 8 - calandre tube; 9 - cold moderator (D_2O); 10 - fuel tube; 11 - liquid fuel.

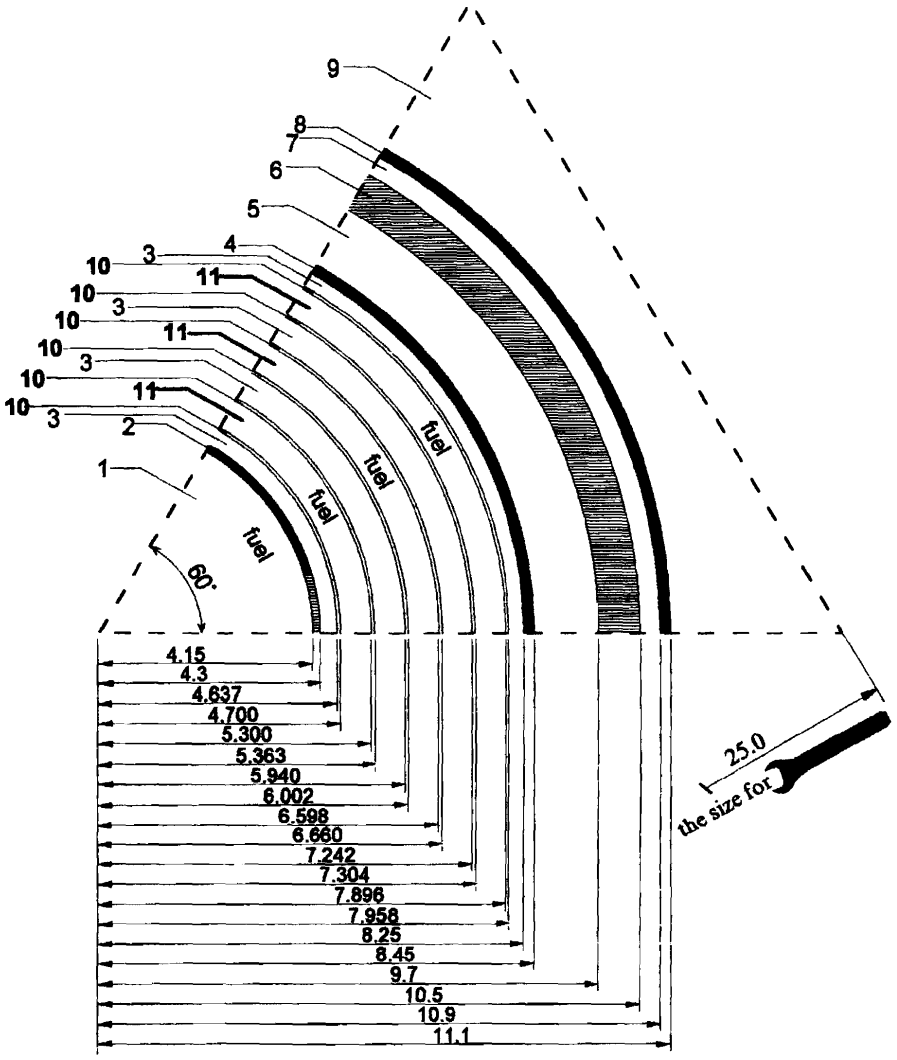

Fig.2. Ring-shaped geometry of the cell (dimensions in cm). 1 - liquid fuel; 2 - central tube for liquid fuel; 3 - moderator (D_2O), zone of heat releasing; 4 - tube separated flows of heat transport heavy water; 5 - cooled volume of heat transport heavy water (zone of heat removal); 6 - load-bearing tube; 7 - heat-insulated gap; 8 - calandre tube; 9 - cold moderator (D_2O); 10 - (Zr+Nb)-layer; 11 - liquid fuel.

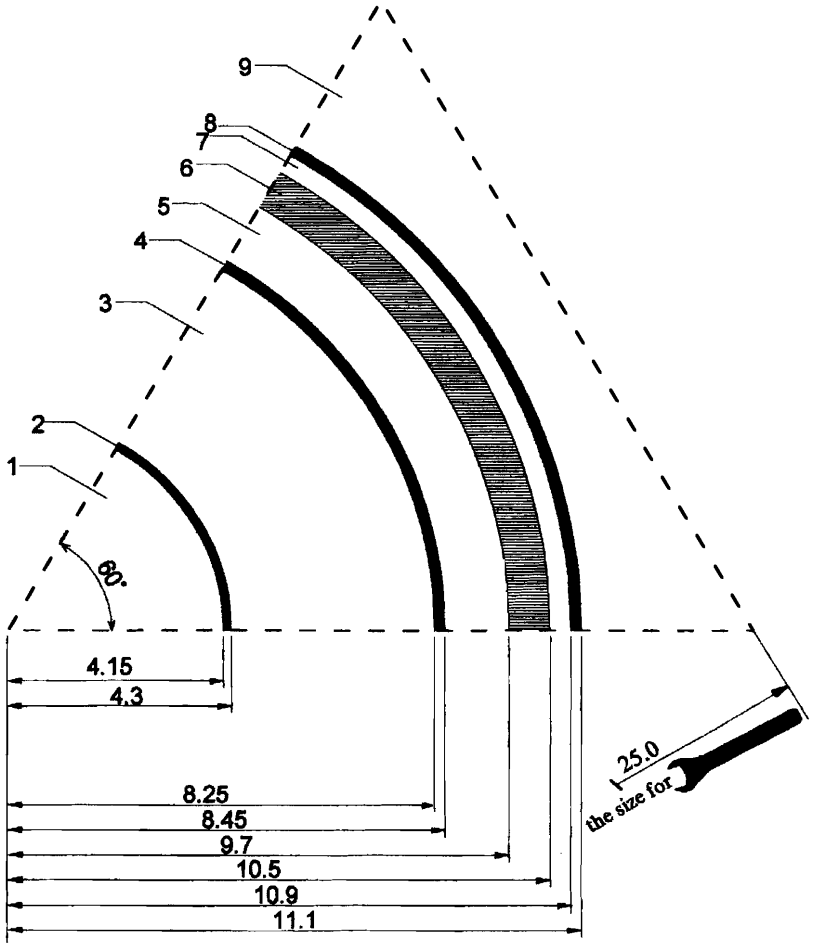

Fig.3. Geometry of the cell (dimensions in cm). 1 - liquid fuel; 2 - central tube for liquid fuel; 3 - zone of homogenization moderator (fuel + D_2O + zirconium-niobium tubes); 4 - tube separated flows of heat transport heavy water; 5 - cooled volume of heat transport heavy water (zone of heat removal); 6 - load-bearing tube; 7 - heat-insulated gap; 8 - calandre tube; 9 - cold moderator (D_2O);

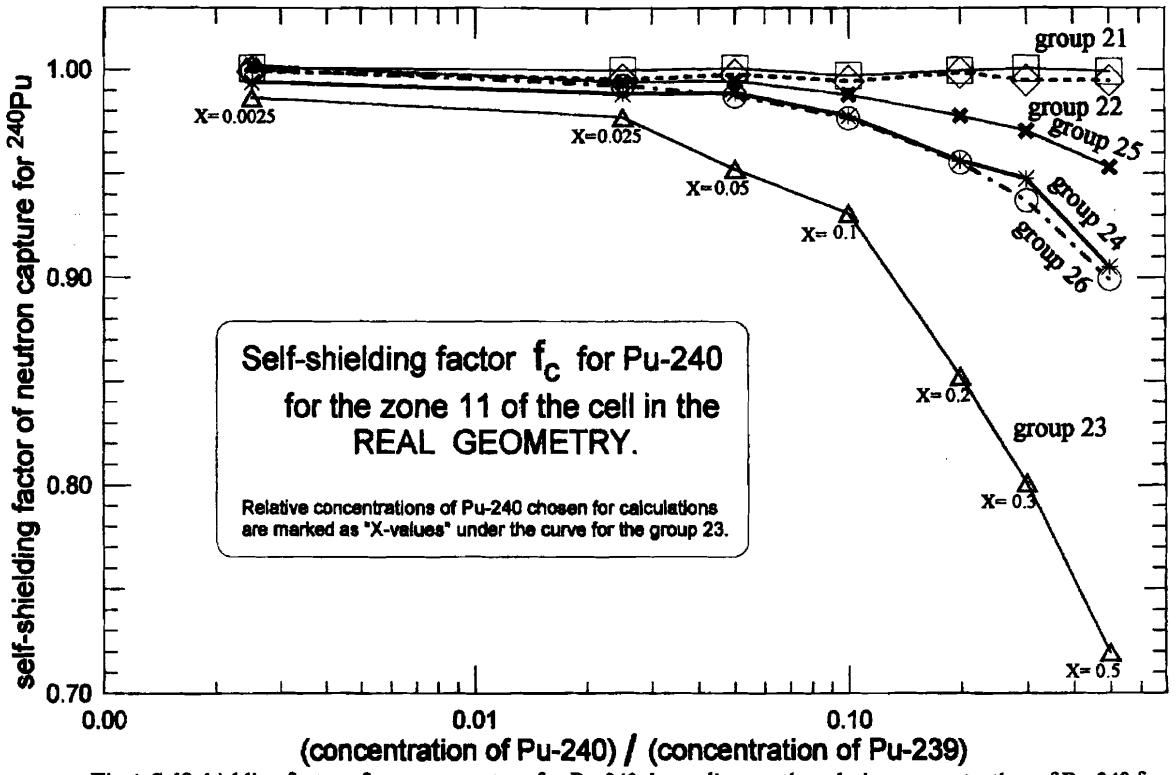

Fig.4 Self-shielding factor of neutron capture for Pu-240 depending on the relative concentration of Pu-240 for different neutron energy group. Results are given for the zone 11 of the cell in the real geometry.

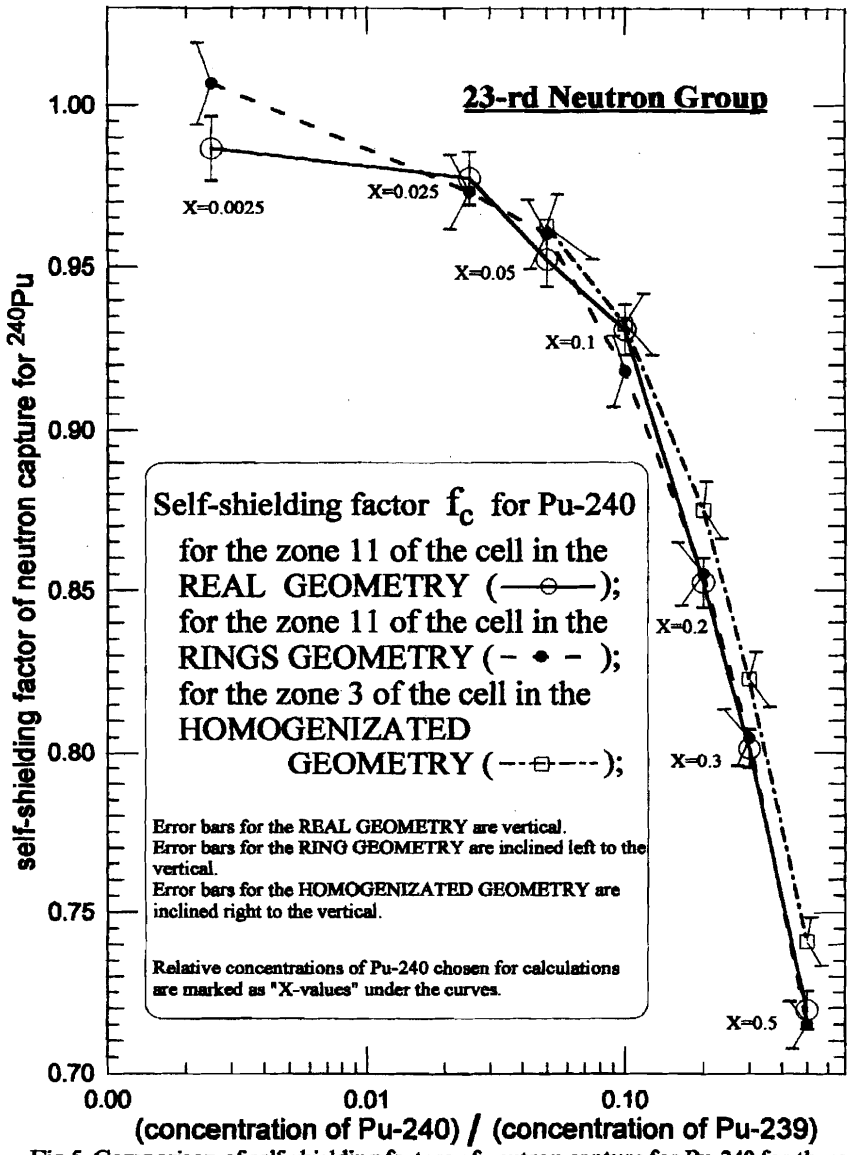

Fig.5 Comparison of self-shielding factors of neutron capture for Pu-240 for three types of the cell geometries (Real, Rings, Homogenization) depending on the relative concentration of Pu-240 for the 23-rd neutron energy group.

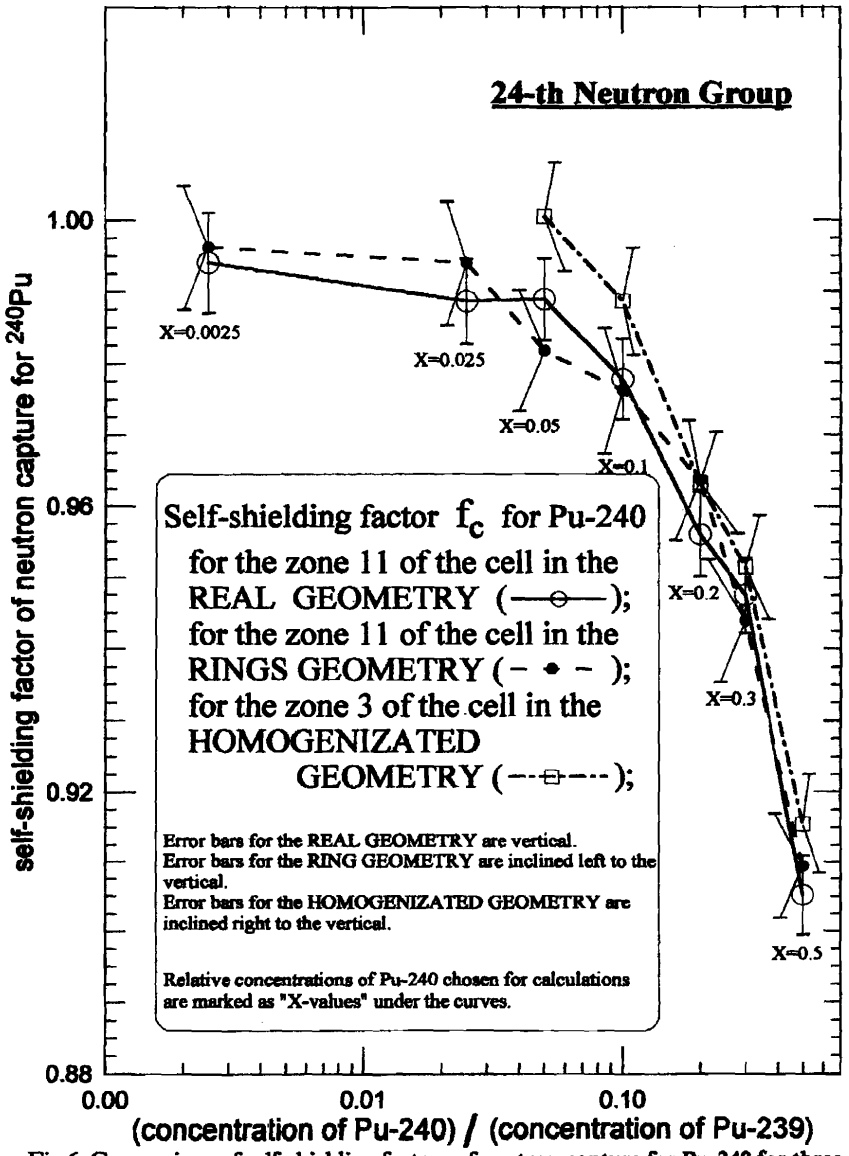

Fig.6 Comparison of self-shielding factors of neutron capture for Pu-240 for three types of the cell geometries (Real, Rings, Homogenization) depending on the relative concentration of Pu-240 for the 24-th neutron energy group.

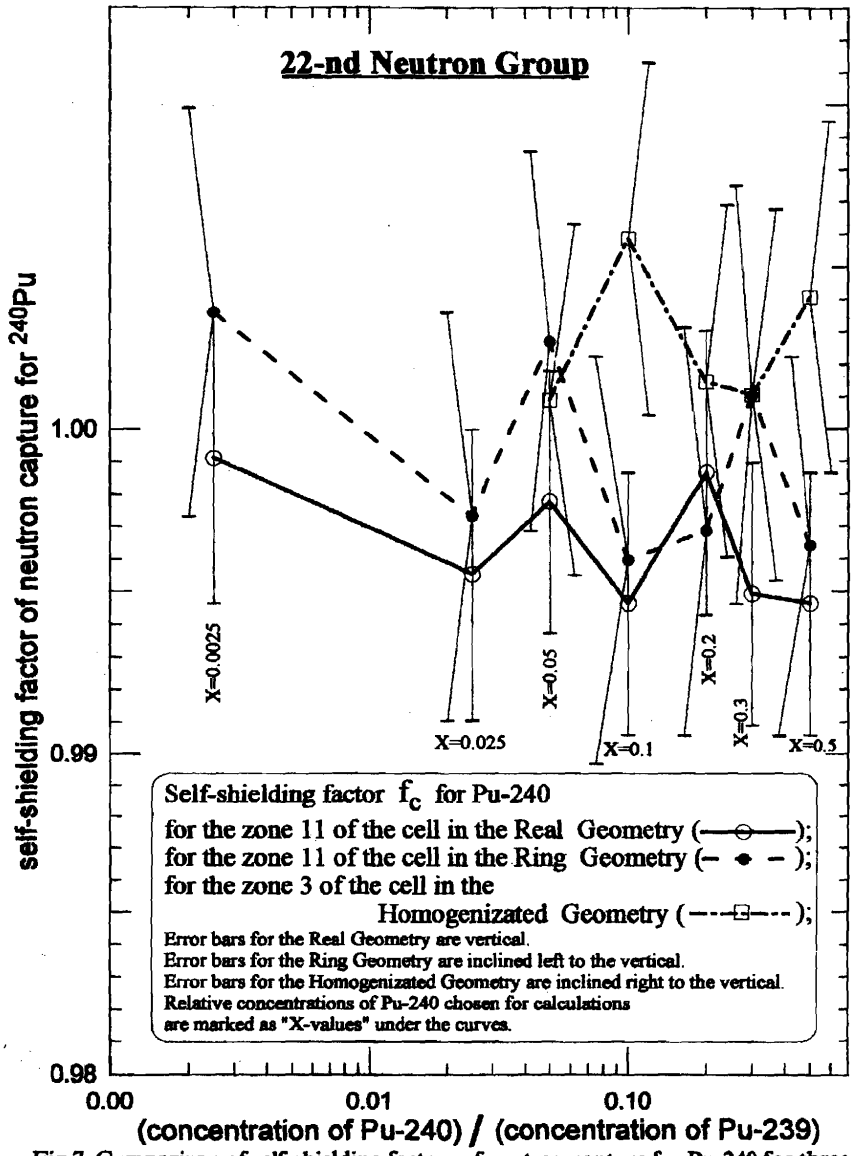

Fig.7 Comparison of self-shielding factors of neutron capture for Pu-240 for three types of the cell geometries (Real, Rings, Homogenization) depending on the relative concentration of Pu-240 for the 21-th neutron energy group.

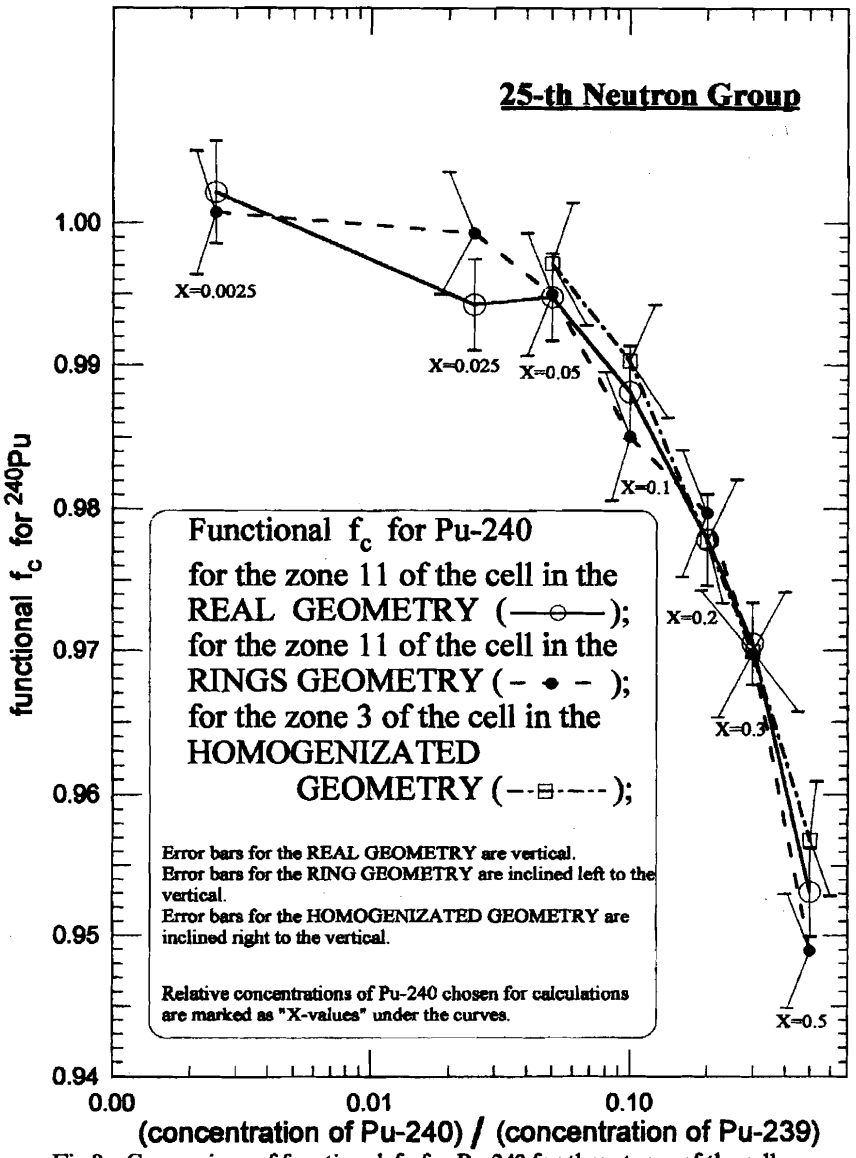

Fig.8 Comparison of functional f_c for Pu-240 for three types of the cell geometries (Real, Rings, Homogenization) depending on the relative concentration of Pu-240 for the 25-th neutron energy group.

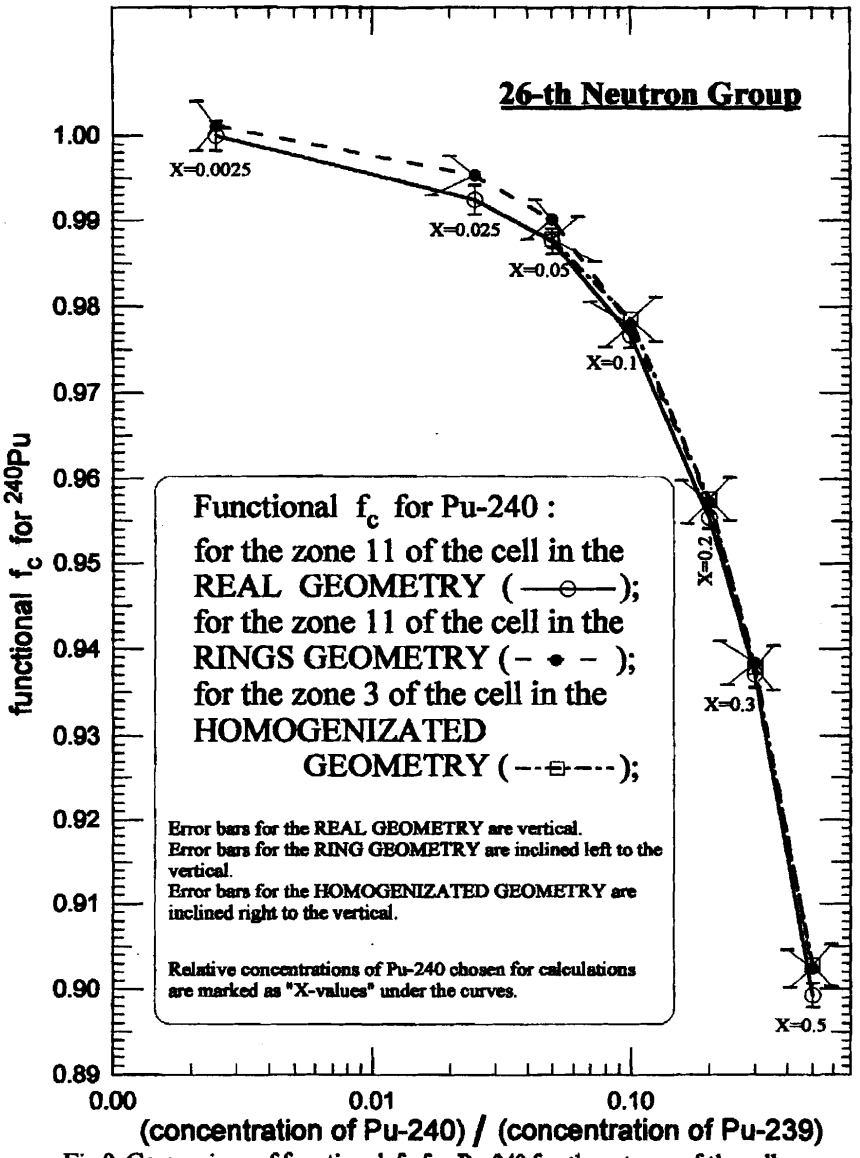

Fig.9 Comparison of functional f_c for Pu-240 for three types of the cell geometries (Real, Rings, Homogenization) depending on the relative concentration of Pu-240 for the 26-th neutron energy group.

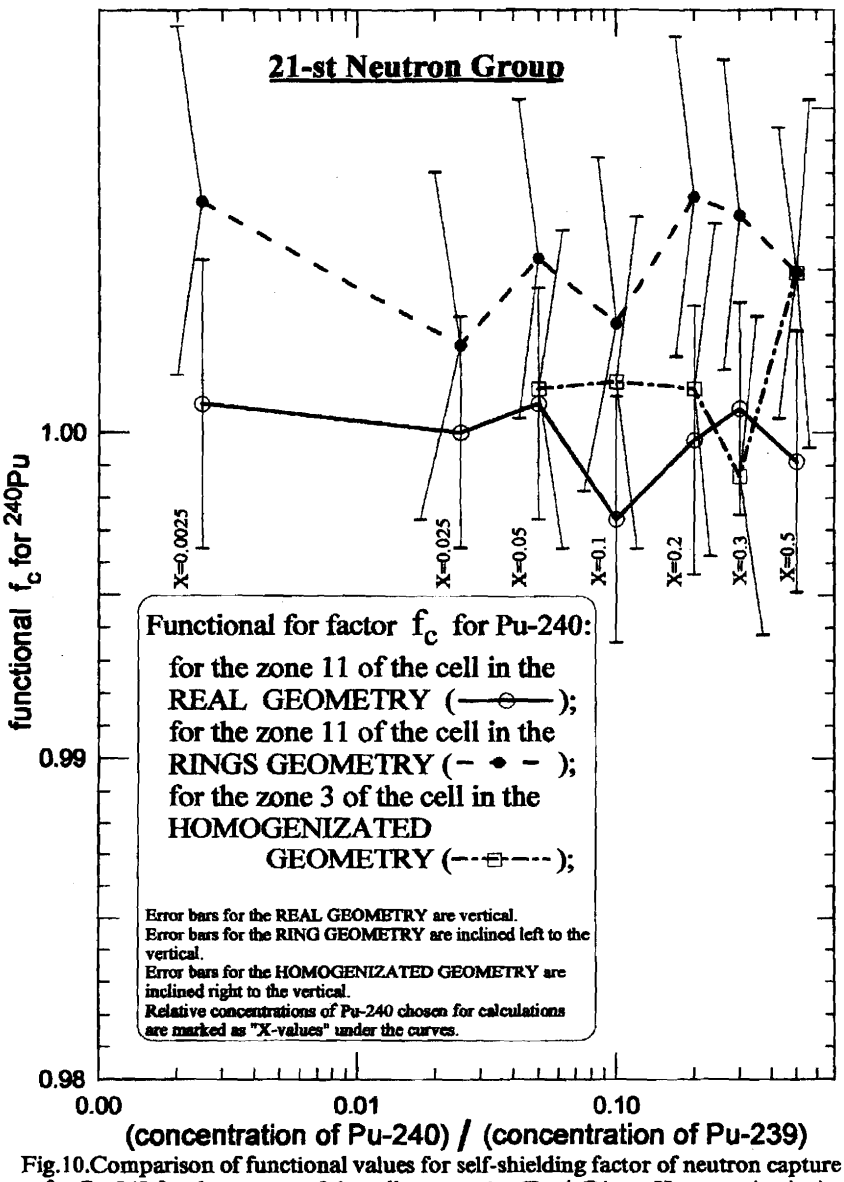

Fig.10.Comparison of functional values for self-shielding factor of neutron capture for Pu-240 for three types of the cell geometries (Real, Rings, Homogenization) depending on the relative concentration of Pu-240 for the 21-st neutron group.

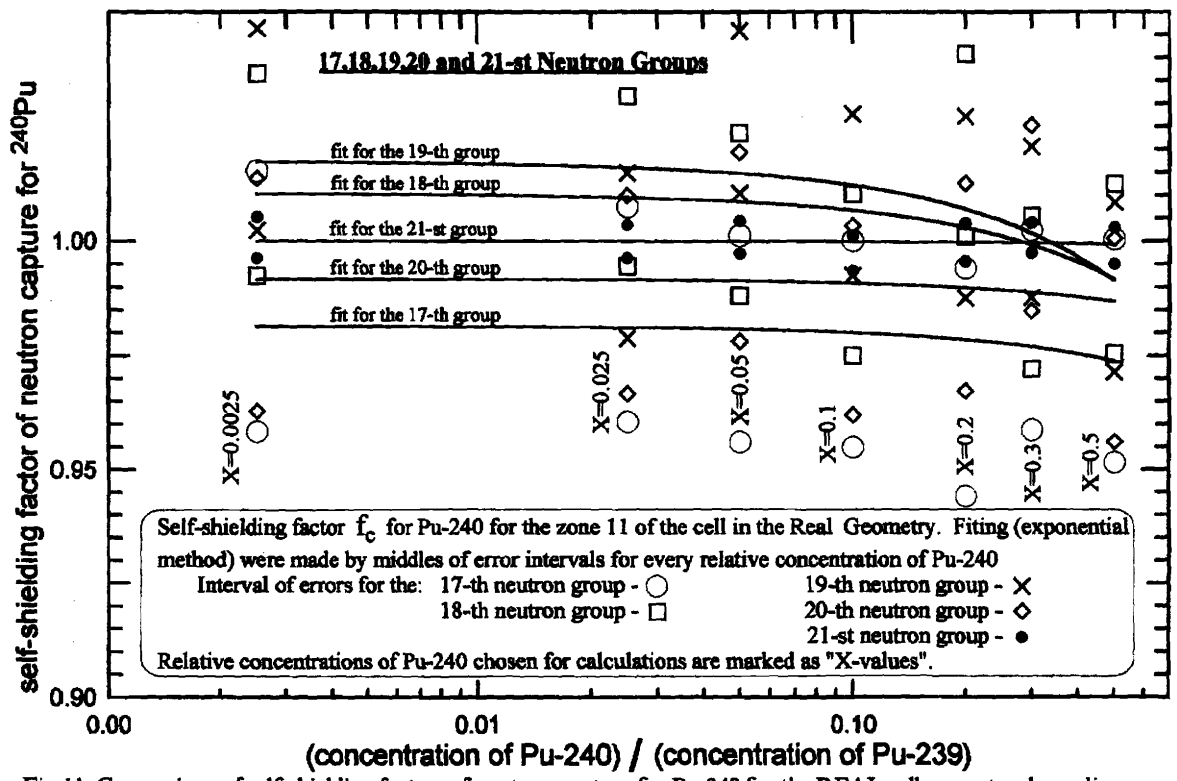

Fig.11 Comparison of self-shielding factors of neutron capture for Pu-240 for the REAL cell geometry depending on the relative concentration of Pu-240 for the 17, 18, 19, 20 and 21-st neutron energy group.

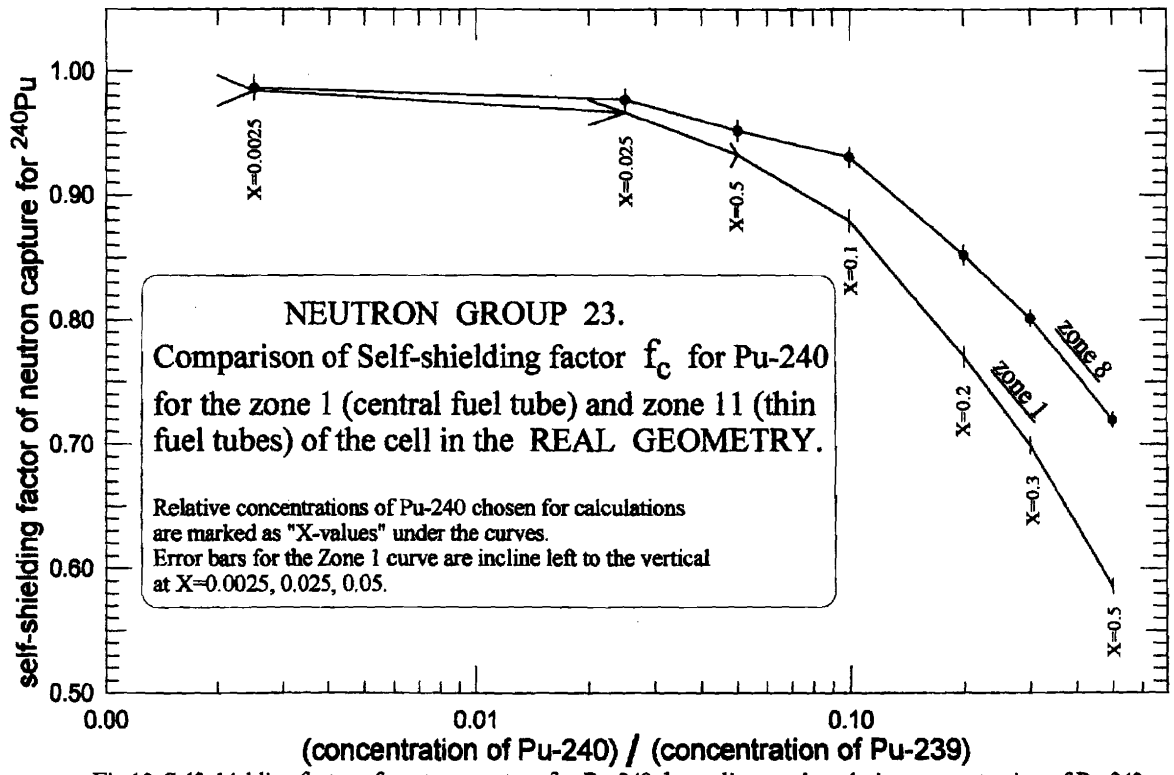

Fig.12 Self-shielding factor of neutron capture for Pu-240 depending on the relative concentration of Pu-240 for 23-rd neutron energy group. Results are given for the zones 1 and 11 of the cell in the real geometry.

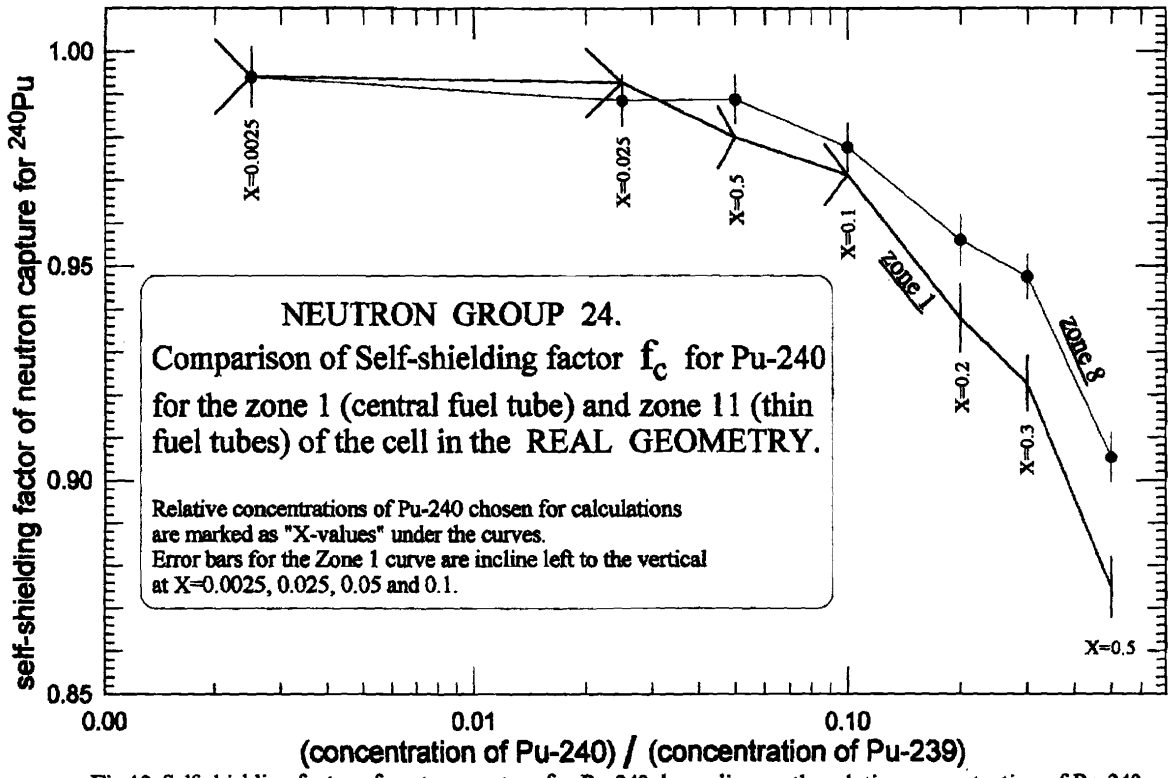

Fig.13 Self-shielding factor of neutron capture for Pu-240 depending on the relative concentration of Pu-240 for 24-th neutron energy group. Results are given for the zones 1 and 11 of the cell in the real geometry.

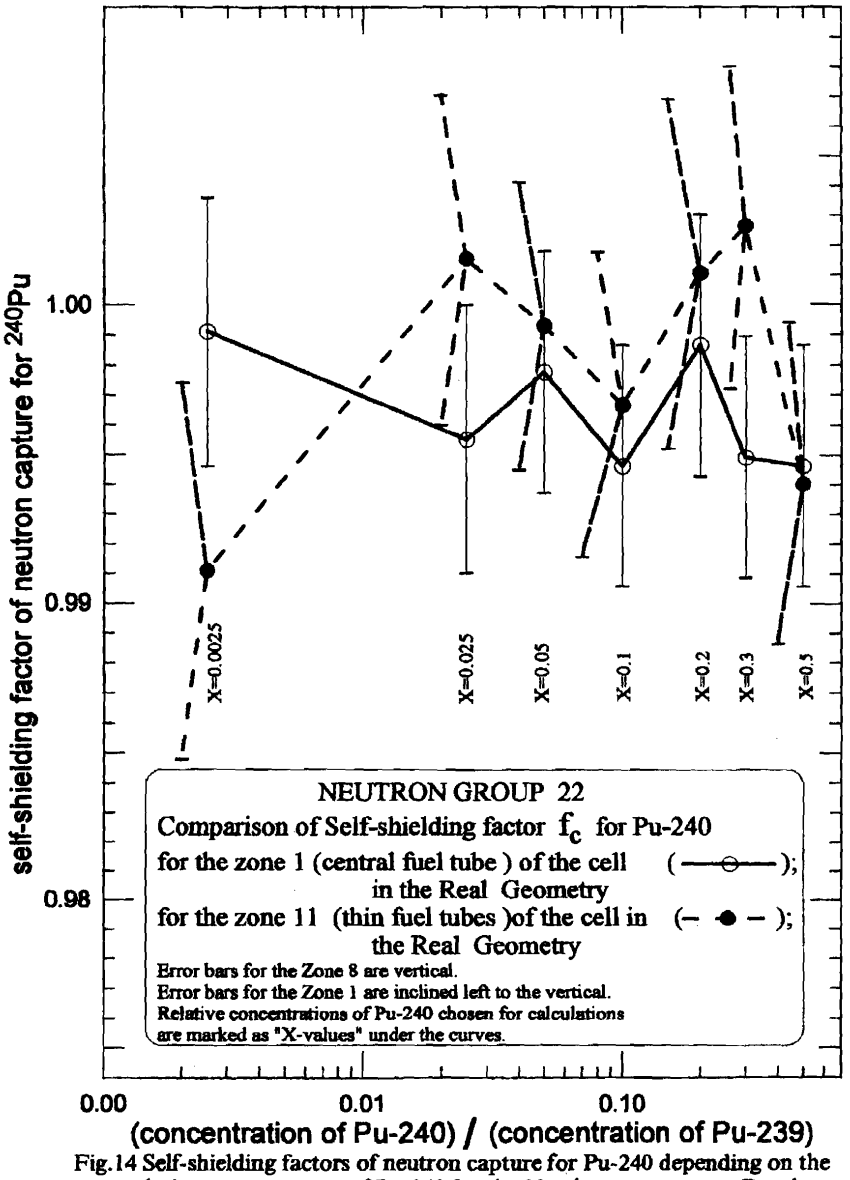

Fig.14 Self-shielding factors of neutron capture for Pu-240 depending on the relative concentration of Pu-240 for the 22-nd neutron group. Results are given for the zones 1 and 11 of the cell in the Real Geometry.

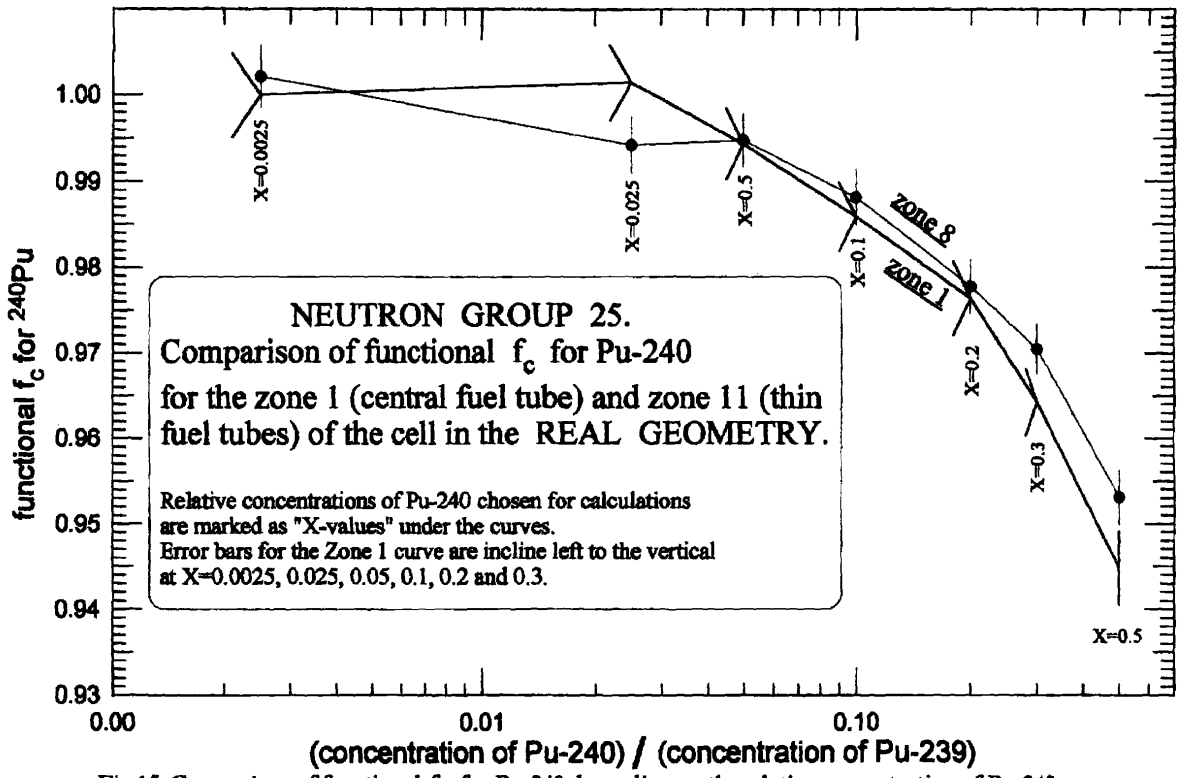

Fig.15 Comparison of functional f_c for Pu-240 depending on the relative concentration of Pu-240 for 25-th neutron energy group. Results are given for the zones 1 and 11 of the cell in the real geometry.

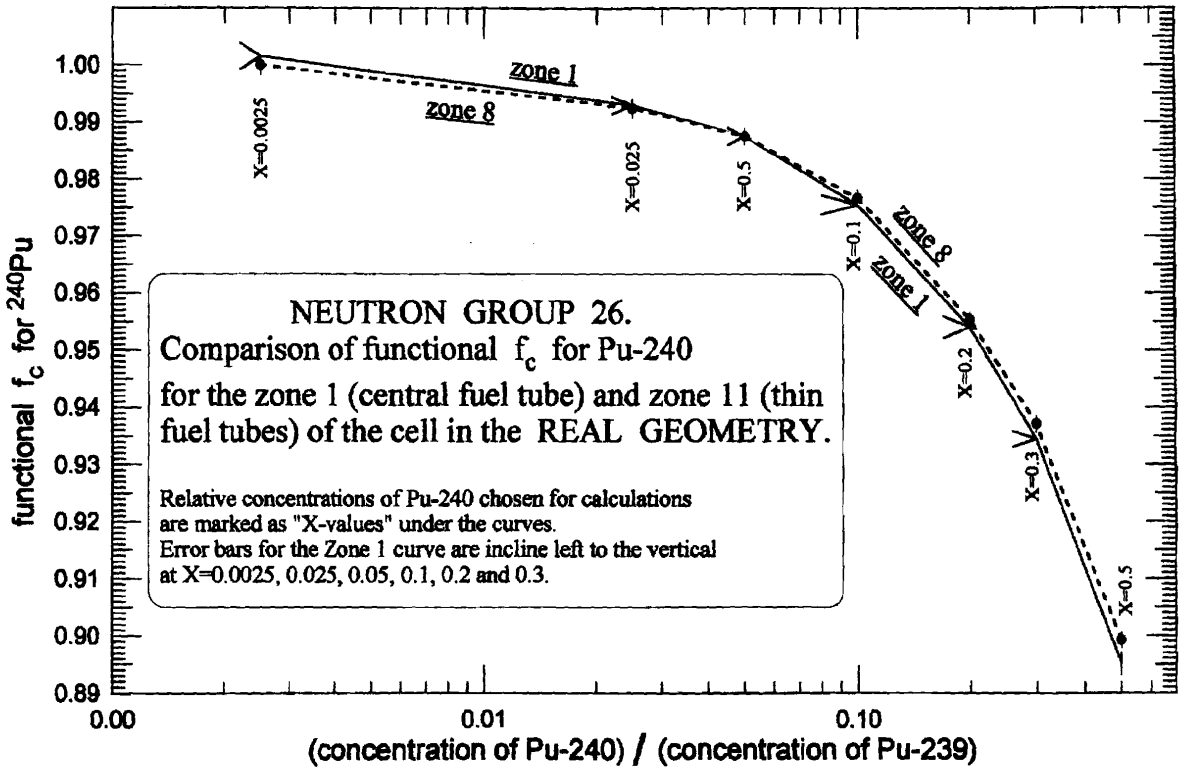

Fig.16 Comparison of functional f_c for Pu-240 depending on the relative concentration of Pu-240 for 26-th neutron energy group. Results are given for the zones 1 and 11 of the cell in the real geometry.

Appendix

Table 1

Nuclear Composition of the Cell Zones for the Real and Ring-shaped Geometry					
ZONE	ISOTOPE	NUCLEAR CONCENTRA-TION	ZONE	ISOTOPE	NUCLEAR CONCENTRA-TION
1	H	2.120E-4	7	O	1.00E-7
	D	5.311E-2			
	O	2.666E-2			
	Pu-239	6.564E-6			
	Pu-240:	see below:			
	X=0.00025	1.641E-9			
	X=0.0025	1.641E-8			
	X=0.025	1.641E-7			
	X=0.05	3.282E-7			
	X=0.1	6.564E-7			
	X=0.2	1.313E-6			
	X=0.3	1.969E-6			
	X-0.5	3.282E-6			
2	Zr	4.250E-2	8	Zr	4.250E-2
	Nb	4.250E-4		Nb	4.250E-4
3	H	2.120E-4	9	H	2.656E-4
	D	5.300E-2		D	6.640E-2
	O	2.700E-2		O	3.333E-2
4	Zr	4.250E-2	10	Zr	4.250E-2
	Nb	4.250E-4		Nb	4.250E-4
5	H	2.120E-4	11	H	2.120E-4
	D	5.312E-2		D	5.311E-2
	O	2.667E-2		O	2.666E-2
				Pu-239	6.564E-6
				Pu-240:	see below:
				X=0.00025	1.641E-9
				X=0.0025	1.641E-8
				X=0.025	1.641E-7
				X=0.05	3.282E-7
				X=0.1	6.564E-7
				X=0.2	1.313E-6
				X=0.3	1.969E-6
				X-0.5	3.282E-6
6	Zr	4.250E-2			
	Nb	4.250E-4			

Appendix

Table 2

Nuclear Composition of the Cell Zones for the Homogenizated Geometry					
ZONE	ISOTOPE	NUCLEAR CONCENTRA-TION	ZONE	ISOTOPE	NUCLEAR CONCENTRA-TION
1	H	2.120E-4	6	Zr	4.250E-2
	D	5.311E-2		Nb	4.250E-4
	O	2.666E-2			
	Pu-239	6.564E-6			
	Pu-240:	see below:			
	X=0.0025	1.641E-8			
	X=0.05	3.282E-7			
	X=0.1	6.564E-7			
	X=0.2	1.313E-6			
	X=0.3	1.969E-6			
	X-0.5	3.282E-6			
2	Zr	4.250E-2	7	O	1.00E-7
	Nb	4.250E-4			
3	H	1.918E-4	8	Zr	4.250E-2
	D	4.800E-2		Nb	4.250E-4
	O	2.427E-2			
	Zr	4.051E-3			
	Nb	4.051E-5			
	Pu-239	2.979E-6			
	Pu-240:	see below:			
	X=0.0025	7.448E-9			
	X=0.05	1.490E-7			
	X=0.1	2.979E-7			
	X=0.2	5.959E-7			
	X=0.3	8.938E-7			
	X-0.5	1.490E-6			
4	Zr	4.250E-2	9	H	2.656E-4
	Nb	4.250E-4		D	6.640E-2
				O	3.333E-2
5	H	2.120E-4			
	D	5.312E-2			
	O	2.667E-2			

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