FEASIBILITY STUDY OF THE WWR-K REACTOR CONVERSION TO LOW-ENRICHED FUEL[1]

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ABSTRACT

Outcomes of the first stage of calculation studies, referring to the eight-tube fuel assembly (FA) and four-tube one (in which the CPS channel shim rod is located), are presented for fuel elements on a base of the UO_2+Al composition with the uranium density 3.0 g·cm^{-3}.

Introduction

Target of nuclear material non-proliferation makes urgent the reduction of fuel enrichment in research reactors – basic consumers of uranium enriched to 36, 80 and 90% in U-235.

By IAEA assessments, uranium enriched in U-235 to less than 20% can't be used in military applications. At this level of enrichment, conservation of the research reactor neutronics parameters is possible only if uranium dioxide (the uranium mass density is not greater than 3.0 g·cm^{-3}) or uranium-molybdenum alloy (the density is not greater than 5.5 g·cm^{-3}), dispersed in aluminum matrix, are used.

In this work results of the first stage of feasibility studies are presented, where the eight-tube and four-tube fuel assemblies (FA) with fuel elements using uranium-dioxide fuel are considered. The uranium density comprises 3 g·cm^{-3}. The reactor core lattice spacing is left 68.3 mm.

Calculations have been performed with the 3D computer codes, which simulate neutron behavior in the reactor core by means of the Monte Carlo technique: the American code MCNP-4/B [1] and the Russian code MCU-REA [2]. Preliminary, these codes have been verified in experiments at the zero-power reactor. Practically, all reactor functionals have been calculated, such as K_{eff}, the CPS worthes, the reactor campaign, the fuel burnup level, the energy deposition density in the reactor core and the thermal/fast flux densities in irradiation channels.

Versions of the reactor core configuration with both the light-water and beryllium reflector have been considered.

Calculation Results

A version of the eight-tube and four-tube fuel assemblies and the reactor core formed from is considered (fig.1). Fuel composition of the fuel assembly IRT-4M [3] is taken as a base.
Below basic parameters of fuel elements and fuel assemblies are given (tables 1 and 2).
The reactor core critical load has been determined. It comprises 11 I-type FA with 10 II-type FA.

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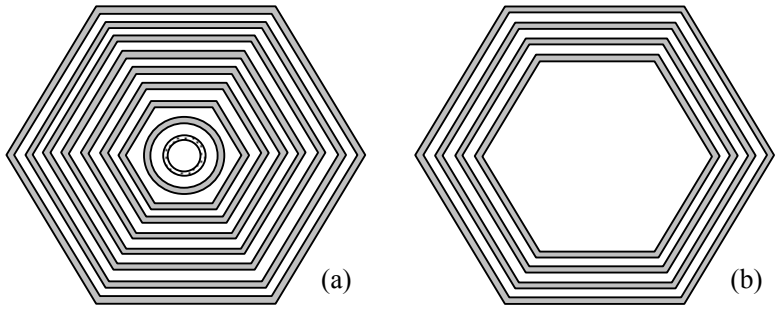


Fig.1. Eight-tube FA (a) and four-tube one (b)

Table 1- Fuel Element Characteristics

First-Type FA				Second-Type FA		
Structure element	Size, mm	Thickness, mm	Mass of U-235, g per FE	Structure element	Size, *mm*	Thickness, mm
FE-1	66.3	1.6	55.6	FE-1	66.3	1.6
FE-2	59.1	1.6	49.4	FE-2	59.1	1.6
FE-3	51.9	1.6	43.3	FE-3	51.9	1.6
FE-4	44.7	1.6	37.1	FE-4	44.7	1.6
FE-5	37.5	1.6	30.9	Rod channel body	38.1	-
FE-6	30.3	1.6	24.7	Rod	33.6	-
FE-7	23.1	1.6	18.5	-	-	-
FE-8	15.9	1.6	11.2	-	-	-
Structural tube	8.8	1.0	-	-	-	-
Fuel element 0.45:0.7:0.45mm Water gap is 2 mm						

Table 2 –Some quantitative characteristics of the eight/four FA

Parameter	FA-I	FA-II
Uranium-235 content in FA, g	270.6	180.4
Watered perimeter, cm	219.1	149.4
Area of heat removal, cm^2	13146.2	8964.0
Water volumetric fraction, %	56.22	-

Basic neutronics characteristics have been calculated for the stages of reactor core initial loading (18 I-type FA and 10 II-type FA, see fig. 2) and stationary loading (34 I-type FA and 10 TBC II-type FA, see fig. 3). Calculation results are presented in Tables 3 and 4. It should be noted that large inaccuracies of the calculated flux densities in peripheral cells are related to insufficient statistics.

As table 3 demonstrates, the net worth of the shim rods and the auto rod doesn't meet the safety requirements (sub-criticality of the reactor core with immersed shim rods and the auto rod should be not less than 1% $\Delta k/k$). Due to this, a series of worth calculations was carried out for shim rods and the auto rod with an enhanced content of boron-10 in the absorbing composition. Results of calculation are given in Table 5.

Table 3 – Neutronics characteristics. Reactor core: 18 I-type FA and 10 II-type FA

Cell #	Position of all SE and SR	Thermal flux density (<0.4 eV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>1.15 MeV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>2.35 MeV), $cm^{-2}\ s^{-1}$
6-5	up	(2.4±0.3) E+14	(4.3±0.9) E+13	(2.1±0.9) E+13
	down	(2.6±0.3) E+14	(4.8±0.5) E+13	(2.4±0.4) E+13
8-5	up	(2.0±0.3) E+14	(3.3±0.8) E+13	(1.7±0.5) E+13
	down	(2.1±0.3) E+14	(3.9±0.8) E+13	(1.9±0.5) E+13
2-2	up	(5.9±0.9) E+13	(4.6±1.3) E+12	(2.6±0.9) E+12
	down	(5.2±1.0) E+13	(4.1±0.9) E+12	(2.4±0.7) E+12
10-2	up	(5.9±1.5) E+13	(4.4±1.2) E+12	(2.3±0.9) E+12
	down	(5.8±1.1) E+13	(4.5±0.9) E+13	(2.5±0.7) E+12
8-1	up	(3.6±0.9) E+13	(3.0±0.9) E+12	(1.8±0.6) E+12
	down	(3.0±1.0) E+13	(2.1±1.7) E+12	(1.5±0.5) E+12
K_{eff}, % Δk/k		ρ, % Δk/k	Σ ρ_{KO+AP}, % Δk/k	Σ ρ_{A3}, % Δk/k
1.0836±0.0002		7.7	7.0	1.8

Table 4 – Neutronics characteristics. Reactor core: 34 I-type FA and 10 II-type FA

Cell #	Position of all SR and AR	Thermal flux density (<0.4 eV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>1.15 MeV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>2.35 MeV), $cm^{-2}\ s^{-1}$
6-5	up	(1.7±0.3) E+14	(3.4±0.8) E+13	(1.7±0.4) E+13
	down	(1.9±0.3) E+14	(3.5±0.8) E+13	(1.6±0.5) E+13
8-5	up	(1.5±0.4) E+14	(2.6±0.8) E+13	(1.3±0.4) E+13
	down	(1.6±0.3) E+14	(3.0±0.9) E+13	(1.5±0.5) E+13
2-2	up	(6.7±1.0) E+13	(9.0±0.0) E+12	(4.6±1.1) E+12
	down	(6.2±1.0) E+13	(9.3±2.5) E+12	(5.1±2.0) E+12
10-2	up	(6.6±1.3) E+13	(8.6±1.2) E+12	(4.6±1.1) E+12
	down	(7.1±1.3) E+13	(1.0±0.4) E+13	(5.0±2.0) E+12
8-1	up	(4.4±0.9) E+13	(3.7±0.9) E+12	(1.9±0.8) E+12
	down	(4.1±1.0) E+13	(3.5±1.4) E+12	(2.1±0.8) E+12
K_{eff}, % Δk/k		ρ, % Δk/k	Σ ρ_{KO+AP}, % Δk/k	Σ ρ_{A3}, % Δk/k
1.1853±0.0002		15.6	7.2	1.8

Table 5 – Worthes of the reactor shim rods and the auto rod versus the B-10 enrichment

Reactor core: 18 I-type FA and 10 II-type FA

Enrichment in B^{10}, %	Position of AR and SR	K_{eff}	$\rho_{r.c.s.}$, % $\Delta k/_K$	Worthes of AR and SR, % $\Delta\kappa/_K$
19.6	up	1.0843 ± 0.0002	7.8	-
	down	1.0069 ± 0.0002	0.7	7.1
40.0	down	0.9957 ± 0.0002	-0.4	8.2
60.0	down	0.9910 ± 0.0002	-0.9	8.7
85.0	down	0.9862 ± 0.0002	-1.4	9.2

Results of calculation show that sub-criticality of the initially loaded reactor core with immersed shim rods and the automate rod comprises 1.4% $\Delta k/_K$ when the enrichment of absorbing composition in boron-10 reaches 85%.

In Tables 6 and 7 values of the energy deposition in FA are presented for two reactor core loading versions. In the first version, the most «hot» FA is located in the cell #7-6, whereas in the second one – in cells 7-6 and 5-6.

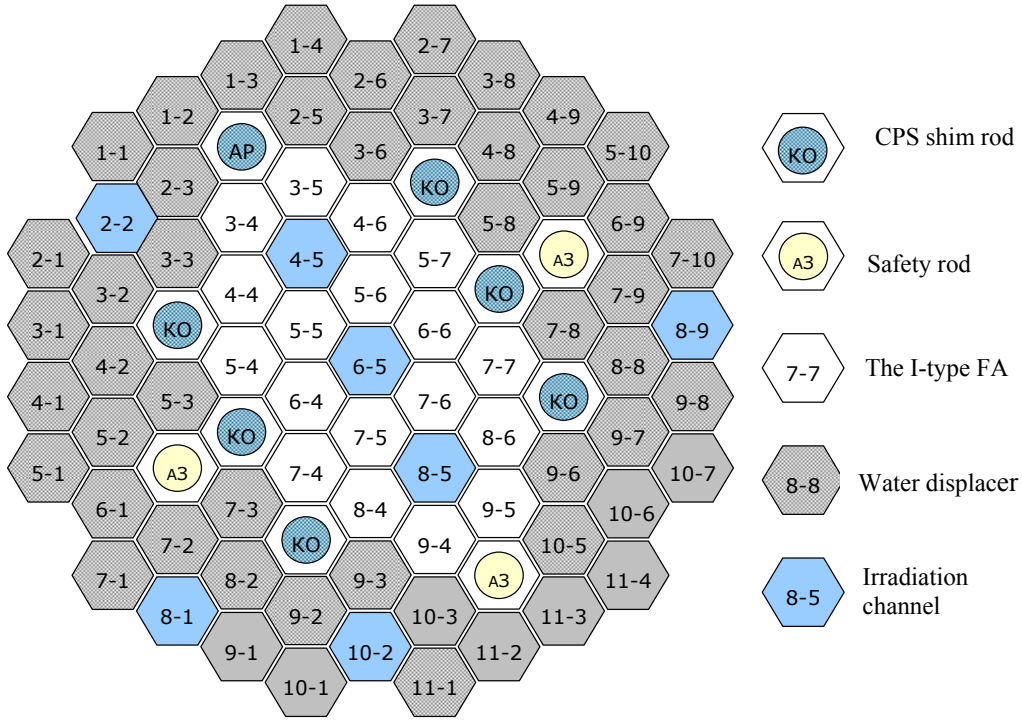


Fig 2. The reactor core initial loading cartogram

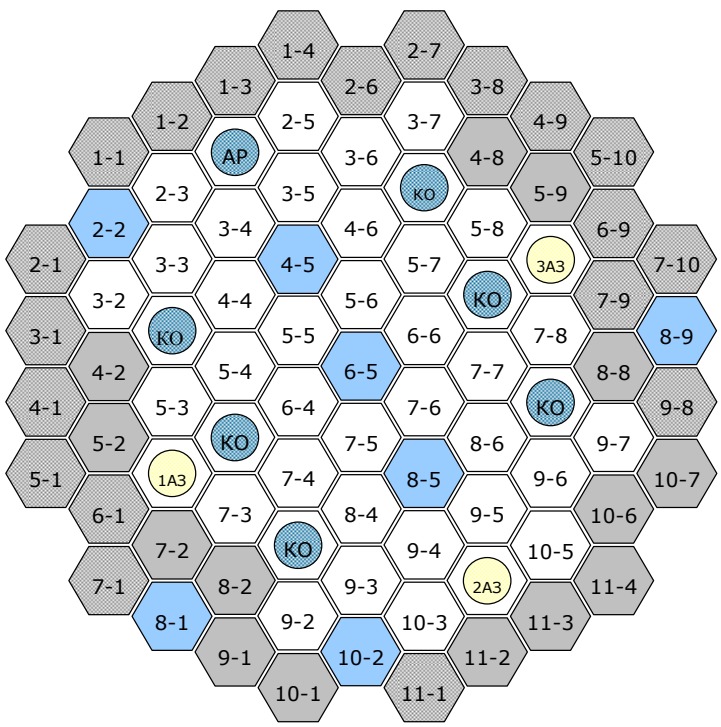


Fig.3. The reactor core stationary loading cartogram

For reactor core initial loading, the operating period and the fuel burnup level have been calculated. An estimate of the accumulated Pu-239 is obtained. After 120 days of reactor operation, 61.4 g of plutonium has been produced in the reactor core. A value of stationary poisoning by Xe-135 is 3.38%(Δk/k) (see fig. 4). Loss of reactivity at the expense of fuel burning up comprises 0.04 %(Δk/k) per 24 hours. The U-235 burnup in the cell having the highest fuel rating is 19.5%. Values of the burnup per FA are given in table 8.

Table 6 – Energy Deposition in the Reactor Core: 18 I-type FA and 10 II-type FA

Cell #	Energy deposition in FA, *kW*		Cell #	Energy deposition in FA, *kW*	
	Reflector: H_2O	Reflector: ***Be***		Reflector: H_2O	Reflector: ***Be***
2-4	111.15	135.56	5-4	221.03	225.87
4-3	164.20	180.68	5-5	321.28	276.64
4-7	166.26	175.25	5-6	316.75	282.11
6-3	159.28	162.37	5-7	231.17	216.22
6-7	164.04	155.69	6-4	281.43	251.76
8-3	166.10	183.32	6-6	282.11	250.16
8-7	163.25	174.01	7-4	218.04	217.59
6-2	150.07	186.89	7-5	314.26	281.66
6-8	153.97	177.11	7-6	322.64	287.13
10-4	105.62	131.15	7-7	228.68	219.62
3-4	205.70	228.25	8-4	227.55	235.32
3-5	211.00	214.67	8-6	234.79	230.30
4-4	239.77	237.38	9-4	202.87	222.61
4-6	236.38	236.69	9-5	200.92	223.84
				6000.0	**6000.0**

Table 7– Energy Deposition in the Reactor Core: 34 I-type FA and 10 II-type FA

Cell #	Energy deposition in FA, *kW*		Cell #	Energy deposition in FA, *kW*	
	Reflector: H_2O	Reflector: ***Be***		Reflector: H_2O	Reflector: ***Be***
2–4	82.63	89.42	5–5	226.86	194.48
4–3	94.80	97.00	5–6	227.83	191.63
4–7	93.04	101.65	5–7	152.32	146.27
6–3	97.11	93.55	5–8	133.66	155.79
6–7	96.17	97.06	6–4	200.05	171.21
8–3	92.81	91.89	6–6	194.48	168.94
8–7	93.97	92.26	7–3	141.78	145.50
6–2	92.07	105.74	7–4	154.24	140.21
6–8	93.44	110.56	7–5	217.94	186.48
10–4	80.78	83.19	7–6	227.54	184.24
2–3	114.22	119.52	7–7	149.44	234.07
2–5	116.42	121.14	7–8	132.71	147.41
3–2	115.04	130.06	8–4	165.24	151.64
3–3	119.04	121.33	8–6	170.38	156.64
3–4	150.29	151.32	9–2	114.82	124.52
3–5	142.26	147.70	9–3	114.63	119.14
3–6	118.10	122.95	9–4	141.97	143.40
3–7	113.81	131.65	9–5	141.59	143.88
4–4	172.90	160.34	9–6	115.94	113.29
4-6	169.58	164.18	9–7	114.63	119.16
5–3	135.36	153.02	10–3	112.21	116.36
5–4	156.06	145.31	10–5	109.64	114.83
				6000.0	**6000.0**

In view of implementation of heat-transfer calculation for the reactor cores with side water reflector, a detailed axial energy distribution was calculated for all fuel elements of the FA having the highest fuel rating (cell 7-6). Calculation results are presented in Figs. 5 and 6.

In fig.6 the specific energy deposition versus the outer fuel element height is shown for various positions of shim rods: the shim rods immersed entirely to the reactor core, immersed to 300 mm, and extracted entirely. For 28 FA loaded, the peaking factors have comprised 1.278, 1.302 and 1.264 respectively, whereas for 44 FA loaded – 1.255, 1.375 and 1.307.

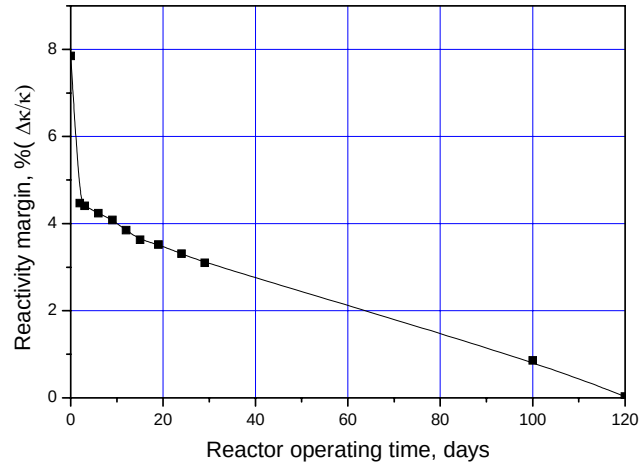
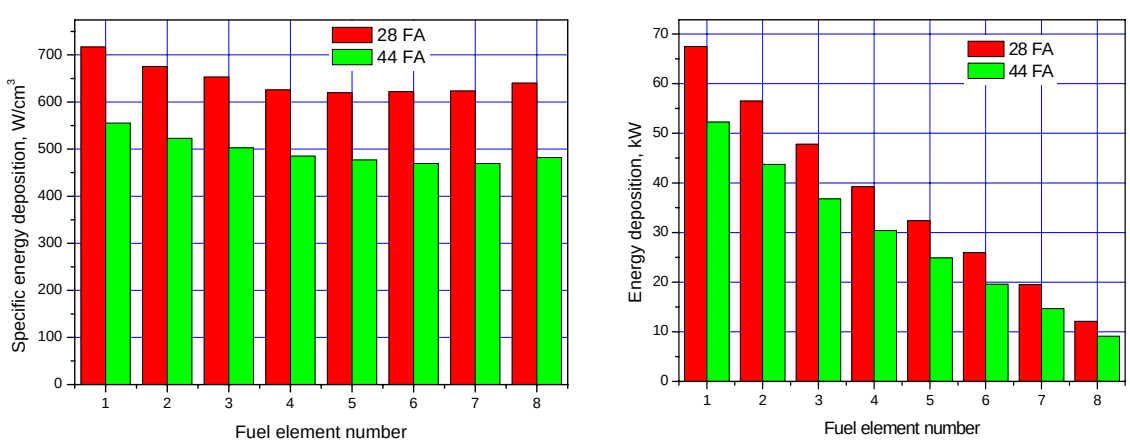


Fig. 4. Reactivity margin versus the reactor operating period at the 6-MW power level

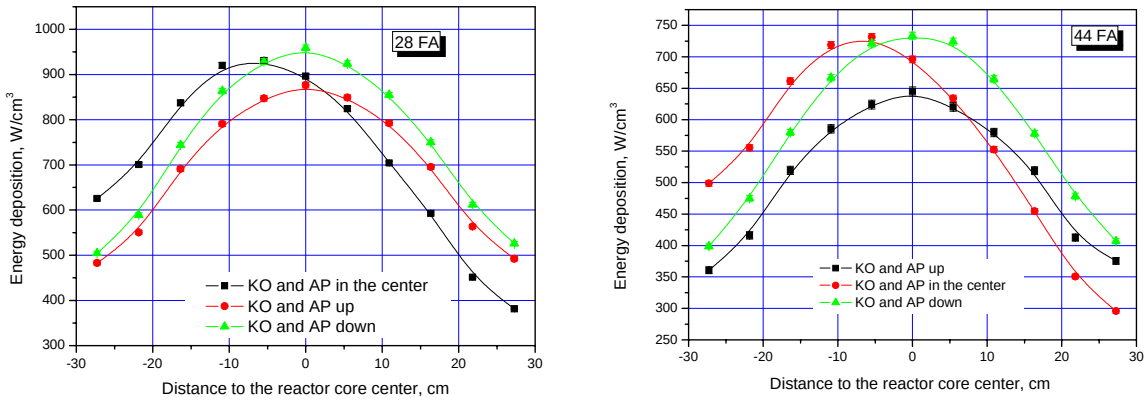
Table 8 – Burnup in the reactor core for 100 days of reactor operation
(18 I-type FA and 10 II-type FA)

Cell #	Burnup in U-235 per FA, %		Cell #	Burnup in U-235 per FA, %	
	Reflector: ***H_2O***	Reflector: ***Be***		Reflector: ***H_2O***	Reflector: ***Be***
2-4	6.70	9.00	(5-4)	9.68	10.08
4-3	9.75	5.92	(5-5)	13.39	12.74
4-7	10.13	11.88	(5-6)	13.63	12.72
6-3	9.95	10.61	(5-7)	9.40	10.21
6-7	9.91	11.06	(6-4)	12.09	11.47
8-3	9.92	11.55	(6-6)	12.13	11.79
8-7	9.80	11.69	(7-4)	9.68	9.80
6-2	9.33	12.22	(7-5)	13.56	12.68
6-8	9.23	12.00	(7-6)	16.27	12.83
10-4	6.94	8.66	(7-7)	9.37	10.24
3-4	8.90	10.31	(8-4)	10.27	10.55
3-5	8.90	10.17	(8-6)	9.93	10.60
4-4	10.13	10.77	(9-4)	8.81	9.86
4-6	10.17	10.97	(9-5)	8.86	10.00



(a) (b)

Fig. 5. Distribution of the specific (a) and total (b) energy deposition over fuel elements for the FA having the highest fuel rating



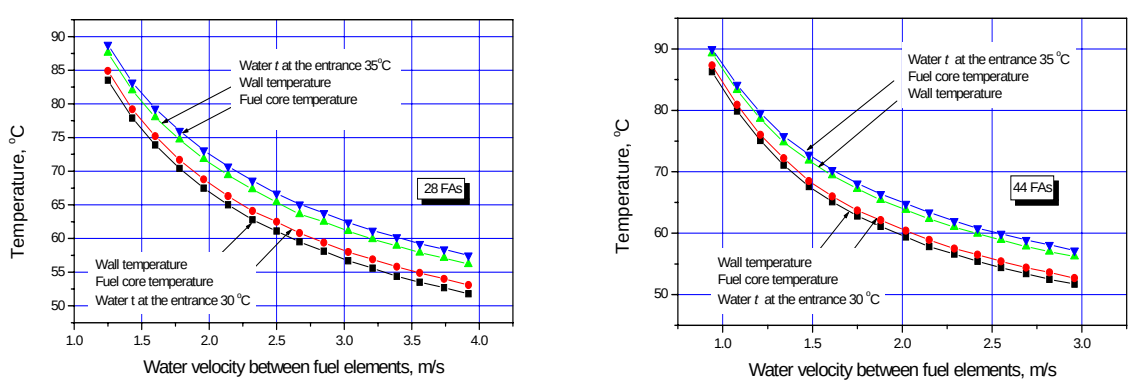
(a) (b)

Fig. 6. Energy deposition versus the height of the outer fuel element for the FA having the highest fuel rating. (a) 28 FAs in the core; (б) 44 FAs in the core

Heat-transfer calculation (the ASTRA [4] code) has been performed for two versions of the reactor corer, mentioned above. As the input data, the following has been used:

- 28 loaded FAs: the reactor core passage cross section for coolant flow, $S_{pass.}$, is 0.07792 m^2;
- 44 loaded FAs: $S_{pass.}$ is 0.10331 $m^{2;}$
- the coolant temperature in the reactor core entrance 30 and 35 °C;
- the water velocity in the FA slots for 28 loaded FAs varies from 1.25 to 3.92 m s^{-1}, corresponding to water discharge rate from 350 to 1100 m^3 h^{-1};
- the water velocity in the FA slots for 44 loaded FAs varies from 0.94 до 2.96 m s^{-1} with the same discharge rate values;
- the maximum specific energy deposition in the fuel core comprises 959 MW m^{-3} for the first version of core loading and 734 MW m^{-3} for the second one.

In fig. 7 the temperature of the fuel core and the FE wall for the highest fuel-rating section versus the water flow velocity is shown. The wall maximum temperature for the 28-FA loading has comprised 87.6 °C; then the water temperature in the exit from FA has reached 64.1°C, and the boiling safety factor is 1.69 (temperature in the entrance is 35 °C). In the second loading version the wall maximum temperature is 89.3°C, the water temperature in the exit is 65.2°C, and the boiling safety factor is 1.60. In both cases water discharge through the reactor core comprises 350 m^3 h^{-1}.



(a) (b)

Fig. 7. Temperatures of the FE wall and fuel core for the FE section having the highest fuel rating versus the water velocity (a) 28 FA, (b) 44 FA

In fig. 8 distribution of the temperature over the FE wall height is shown for two loading version, and the maximum thermal flux density has comprised 327 and 257 kW m^{-2} respectively.

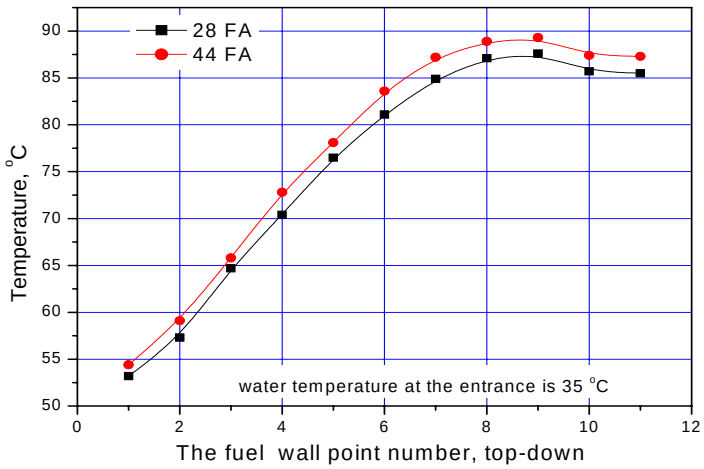


Fig. 8. Temperature in points of a wall of the fuel element having the highest fuel rating, beginning with entrance to FA

Calculations have shown that the limiting heat-transfer parameters for the eight-tube FA (due to a developed energy-conduction surface) aren't reached in version of both the reactor core initial and stationary loading.

For two versions of the reactor core loading with eight/four-tube FAs neutronics characteristics have been calculated with the water side reflector changed by the beryllium one. The side beryllium reflector is formed from units having external sizes similar to those of FA; the beryllium mass density was assumed to be equal to 1.85 g cm^{-3}. In the first case 18 I-type FA and 10 II-type FA enter the reactor core; the beryllium reflector is composed of 48 modular units. In the second case (see fig. 9) the reactor core is composed of 34 I-type FA and 10 II-type one, and 32 beryllium units represent beryllium side reflector.

Neutron characteristics for the cases mentioned above are presented in Tables 9 and 10.

Table 9 – Neutron characteristics of the reactor core composed of 18 I-type FA and 10 II-type FA and side reflector –48 units of beryllium

Cell #	Position of all SE and SR	Thermal flux density (<0.4 eV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>1.15 MeV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>2.35 MeV), $cm^{-2}\ s^{-1}$
6-5	up	(2.3±0.3) E+14	(3.8±0.9) E+13	(2,0±0,6) E+13
	down	(2.5±0.3) E+14	(4.3±0.9) E+13	(2,0±0,4) E+13
8-5	up	(1.9±0.3) E+14	(3.3±0.8) E+13	(1,5±0,5) E+13
	down	(2.3±0.3) E+14	(4.0±0.9) E+13	(1,8±0,4) E+13
2-2	up	(1.0±0.3) E+14	(4.3±1.1) E+12	(2,0±0,7) E+12
	down	(8.3±1.0) E+13	(3.9±1.2) E+12	(1,6±0,4) E+12
10-2	up	(1.0±0.3) E+14	(4.1±1.2) E+12	(1,5±0,5) E+12
	down	(1.0±0.3) E+14	(4.4±1.4) E+12	(2,1±0,8) E+12
8-1	up	(7.6±1.9) E+13	(2.7±0.9) E+12	(1,0±0,4) E+12
	down	(6.0±1.0) E+13	(2.4±0.7) E+12	(8,1±2,5) E+11
K_{eff}, % Δk/k		ρ, % Δk/k	Σ ρ_{KO+AP}, % Δk/k	Σ ρ_{AZ}, % Δk/k
1.2320±0.0002		18,8	9.7	2.5

Table 10 – Neutron characteristics of the reactor core composed of 34 I-type FA and 10 II-type FA and side reflector – 32 units of beryllium

Cell #	Position of all SE and SR	Thermal flux density (<0.4 eV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>1.15 MeV), $cm^{-2}\ s^{-1}$	Fast neutron flux density (>2.35 MeV), $cm^{-2}\ s^{-1}$
6-5	up	(1.6±0.3) E+14	(3.0±0.7) E+13	(1.5±0.4) E+13
	down	(1.8±0.3) E+14	(3.1±0.8) E+13	(1.6±0.4) E+13
8-5	up	(1.4±0.2) E+14	(2.4±0.6) E+13	(1.2±0.3) E+13
	down	(1.5±0.3) E+14	(2.8±0.9) E+13	(1.4±0.5) E+13
2-2	up	(8.6±1.0) E+13	(1.1±0.2) E+13	(5.2±1.1) E+12
	down	(9.3±1.0) E+13	(1.3±0.4) E+13	(5.6±1.5) E+12
10-2	up	(8.3±1.3) E+13	(1.1±0.4) E+13	(4.8±1.3) E+12
	down	(8.9±1.3) E+13	(1.3±0.4) E+13	(5.0±1.5) E+12
8-1	up	(6.9±0.9) E+13	(2.9±0.9) E+12	(1.8±0.6) E+12
	down	(7.4±1.0) E+13	(3.0±1.4) E+12	(2.1±0.7) E+12
K_{eff}, %(Δk/k)		ρ, % Δk/k	$\Sigma\ \rho_{KO+AP}$, % Δk/k	$\Sigma\ \rho_{A3}$, % Δk/k
1.2779±0.0002		21.7	8.1	2.4

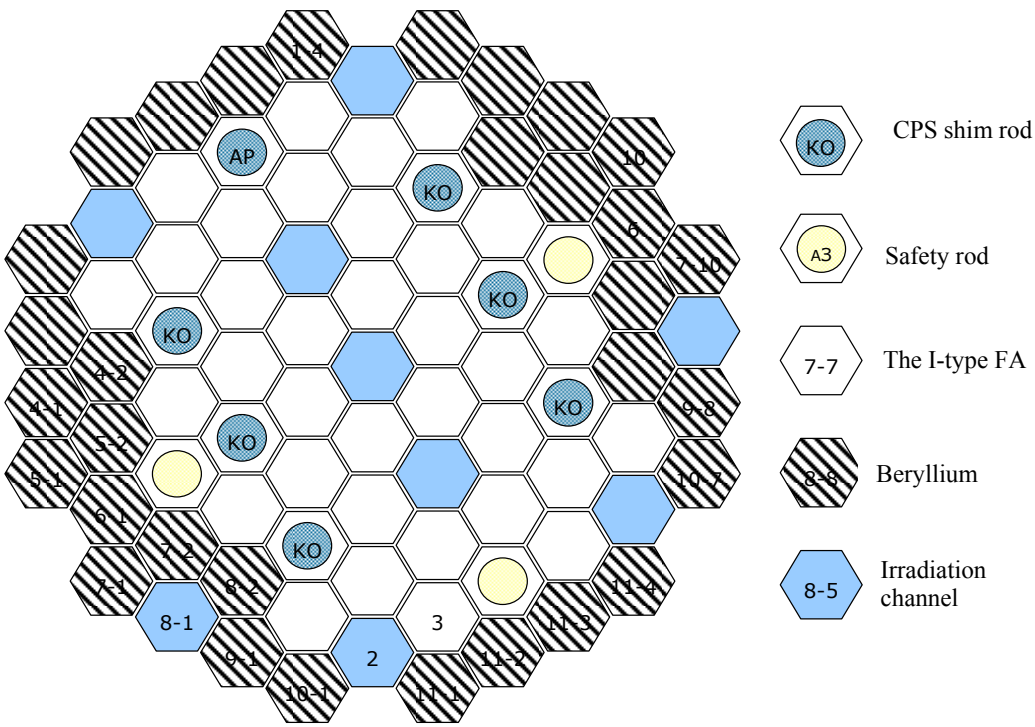


Fig. 9. The reactor core stationary loading cartogram with beryllium reflector

Values of the energy deposition and the fuel burnup level in FA are presented in Tables 6, 7 and 8. In contrast to the reactor core with light-water reflector, four fuel assemblies located in the cells 5-5, 5-6, 7-5, and 7-6 have the maximum fuel rating. The maximum burnup level for 300 days of reactor operation has comprised 37%; a value of stationary poisoning is 3.0% Δk/k; loss of reactivity at the

expense of fuel burning up comprises 0.04 %(Δk/k) per 24 hours, a mass of the produced plutonium is 170 g.
As for the version with light-water reflector, large irregularity in the energy distribution over the reactor core is typical, and, in terms of heat-transfer, it is inferior in this respect to the considered version, so calculation for it wasn't performed.

Conclusion

The version of the WWR-K reactor conversion to low-enriched fuel on a base of the UO_2+*Al* composition is considered. It is shown that at both stages of initial and stationary loading of the reactor core the proposed version, by its experimental characteristics (the neutron flux density, the number of experimental channels, etc.) and operational indices (the burnup level, opportunity to prolong the reactor operational period) surpasses the existing reactor core.

Transition to a version with a side reflector made of beryllium can be implemented successively after realization of cycles with initial loading of the reactor with a water reflector.

In close future the studies with the pin fuel elements on a base of the compositions UO_2+*Al* and *UMo*+*Al* [5] are assumed to be implemented.

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