CHARACTERISTICS OF THE WWR-K REACTOR CORE WITH LOW-ENRICHED URANIUM DIOXIDE FUEL*

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The neutronics and thermal-hydraulic characteristics of the core with eight- and five-tube FAs are presented. The FA face-to face size is 66.3 mm. The net loads of uranium-235 per the eight-tube FA (FA-1) and the five tube FA (FA-2) are ~253 and ~202 g respectively. Five-tube FAs are intended to arrange original channels of the operational elements of the WWR-K CPS. The uranium density of the UO_2-Al fuel meat material is 2.8 g·cm^{-3}.

The core initial charge is 16 FA-1 and 10 FA-2 (including three AZ shut-down elements, six KO shim elements and the AP automate control element) with the reactivity margin comprising 7.2%Δk/k and the net CPS worthies comprising 9.0%Δk/k (KO and AP) and 2.7%Δk/k (AZ). For the 6-MW power rating, the thermal neutron flux density in the core central channels and in the channels located in the reflector comprise, respectively, ~$2.1\cdot10^{14}$ and ~$5.0\cdot10^{13}$ cm^{-2}·s^{-1}; the reactor operation cycle reaches 90 days.

Around the core the side beryllium reflector is formed from beryllium pieces step by step, by portions determined by he net efficiency of the shim elements KO and the automate rod (AP). With 24 beryllium pieces (a single row around the core) and the 50-% peak burnup achieved, the net operation cycle duration reaches ~320 days. The thermal neutron flux density in the reflector channels has increased up to $7.2\cdot10^{13}$ cm^{-2}·s^{-1}. The CPS control rod efficiency has increased up to 11.4%Δk/k - for KO and AP, and up to 4.7%Δk/k – for AZ.

Further, as the FAs burnt off are unloaded, beryllium blocks are loaded instead, up to 52 pieces (full occupation of the free core cells). The net efficiency of KO and AR has increased up to 12.4%Δk/k; the thermal neutron flux density in the reflector channels has comprised ~$9.3\cdot10^{13}$ cm^{-2}·s^{-1}.

Thermal-hydraulic calculations have proved the core heat-engineering reliability.

Following results of analysis of the neutron-physical characteristics of the core versions differing in fuel compositions and the FE and FA designs [1-3], the eight-tube FA-1 and five-tube FA-2 with UO_2-Al fuel having the uranium density 2.8 g·cm^{-3} are recognized as the optimum. The meat is 0.7 mm thick. The FA-2 design parameters make it possible to use the WWR-K reactor existing CPS operational elements. Characteristics of FAs are presented in Table 1; the FA cross sections are shown in Fig.1.

Table 1 – Characteristics of the FA-1 and FA-2.

FA-1	Size, mm	Thickness, mm	U-235 mass, g	FA-2	Size, mm	U-235 mass, g
FE-1	66.3	1.6	51.9	FE-1	66.3	51.9
FE-2	59.1	1.6	46.2	FE-2	59.1	46.2
FE-3	51.9	1.6	40.4	FE-3	51.9	40.4
FE-4	44.7	1.6	34.6	FE-4	44.7	34.6
FE-5	37.5	1.6	28.8	FE-5	37.5	28.8
FE-6	30.3	1.6	23.0	CPS CR channel	32	-
FE-7	23.1	1.6	17.3	CPS CR	27	-
FE-8	15.9	1.6	10.4	-	-	
Structural tube	8.8	1.0	**Total: 252.6**	-	-	**Total: 201.9**

* Work was performed with financial support from NTI

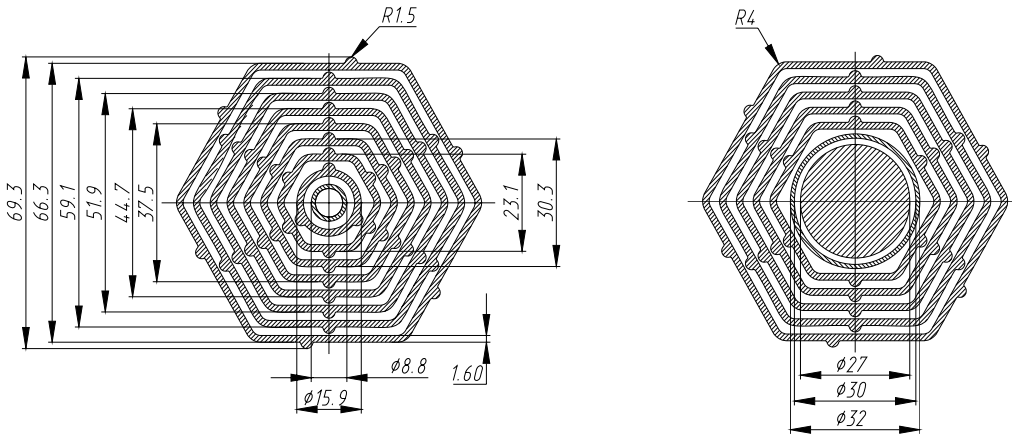

Figure 1. Cross sections of FA-1 and FA-2

Initial fresh core with 16 eight-tube fuel assemblies (FA-1), 10 five-tube ones (FA-2) and the side water reflector, denoted as “16+10”, is given in Fig.2. The appropriate K_{eff} comprises 1.0778(3). (Calculations of neutron-physical characteristics are performed with the code MCU-REA [4].)

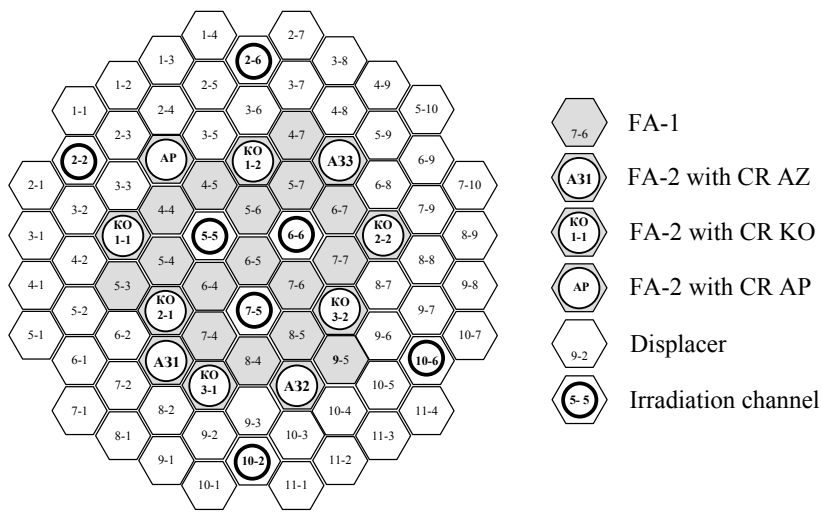

Figure 2. The initial core cartogram«16+10»

Calculated efficiencies of all groups of control rods (CR) of the reactor control and protection system (CPS), with interference between them taken into account, are presented in Table 2.
(A couple of shim elements per drive is assumed to be allocated.)

Table 2. CPS CR efficiencies

Parameters	Core configuration «16+10»		
K_{eff}, ρ	1.0778(3), 7.21%(Δk/k)		
K_{eff}, ρ , KO+AP ↓↓ (CR efficiencies)	0.9830(2), -1.73%, 9.0 %		
K_{eff}, ρ, AZ↓↓↓ (CR efficiency)	1.0476(3), 4.54%, 2.67 %		
KO1↓↓	1.0525(5), 2.2 %		
KO1-1 ↓ KO1-2 ↓	1.0670(3), 0.92%	1.0617(3), 1,3 %	
KO 2 ↓↓	1.0497(5), 2.48 %		
KO 2-1 ↓ KO 2-2 ↓	1.,73 %	0.,65 %	
KO 3 ↓↓	1.0511(5), 2.35 %		
KO 3-1 ↓ KO 3-2 ↓	0.76 %	1.43 %	
AZ ↓↓↓	1.0476(3), 2.67 %		
AZ1 ↓, AZ2 ↓, AZ3 ↓	0.94 %	0.71 %	0.81 %
AP efficiency	1.0694(5), 0.7 %		

*↓ CR is down

To make sure that the net efficiency of the CPS control rods is sufficient when managing emergency situation, we have considered a case of spontaneous withdrawal of the most effective shim element (KO) followed by wedging the most effective protection rod (AZ), provided:

- The core reactivity margin comprises 7.2%Δk/k at the coolant temperature 20˚C.
- The reactor power rating is 6 MW; the inlet and in-core coolant temperatures are 35 and 42˚C respectively; the temperature effect at the expense of coolant heating is negative, equal to 0.3 %Δk/k; hence, the reactivity margin will comprise 6.9 %Δk/k when the coolant is heated up to 45.4˚C.
- Efficiency of simultaneously immersed shim elements (KO1, KO2, KO3) and the automate rod (AP) is 9.0 %Δk/k; the reactor subcriticality with all CPS control rods immersed equals 4.9 %Δk/k.
- Spontaneous withdrawal of the most efficient shim element (KO2) occurs. When all CPS control rods, at the except of the most efficient protection rod (AZ1), are immersed, the KO2 efficiency is 3.3 %Δk/k).
- The rate of introduction of positive reactivity is 0.07 $\beta_{eff}\cdot s^{-1}$; the time of introduction of positive reactivity, 3.3 %Δk/k, comprises ~62 s.
- Wedging of the most efficient protection rod (AZ1) occurs; its efficiency is 0.9 %Δk/k;
- By emergency protection signal, the protection rods AZ2 and AZ3 are dropped, the shim elements KO1 and KO3 are immersed completely, and the automate rod (AP) – by a half. Thus, full immersion of the rods KO1, KO3, AP, AZ2 and AZ3 introduces the negative reactivity equal to 4.0 %Δk/k.
- Efficiency of the rods AZ2 and AZ3 with the KO2 and AZ1 withdrawn comprises 2.1%Δk/k.
- the time needed to introduced emergency protection is 0.7 s.
- the time needed to immerse undipped portions of the AP rod and the shim elements KO1 and KO3 also is assumed to be equal to 0.7 s; the time of emergency signal delay is 0.3 s.
- β_{eff} = 0.785 %; the lifetime of prompt neutrons is $5.5\cdot10^{-5}$ s.
- the reactivity temperature factor is negative, equal to 0.015%Δk/k per degree of Celsium.

Patterns of temporal variations in the reactor power and the FE wall temperature are illustrated by figures 3 and 4.

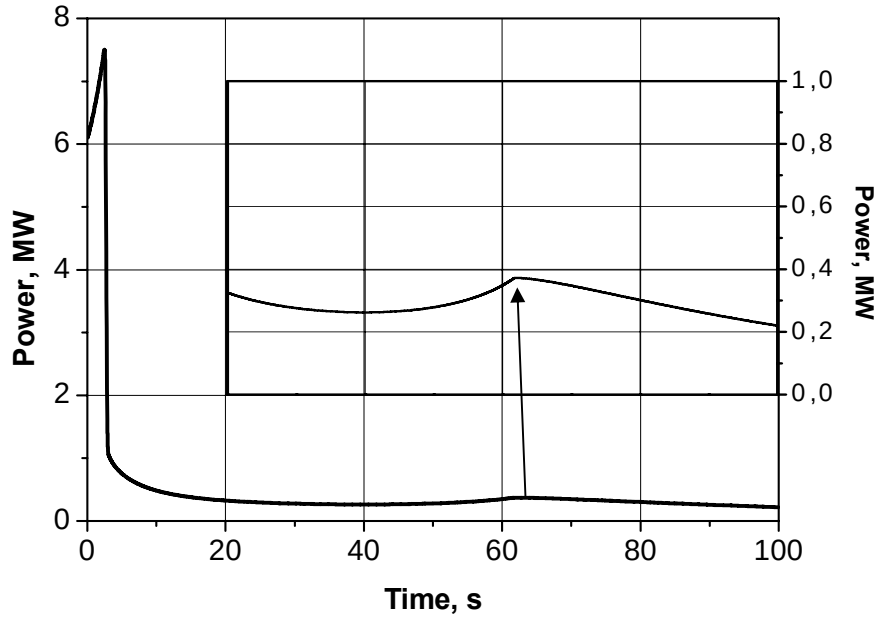

Figure 3. The reactor power versus time, in course of spontaneous withdrawal of the shim element KO2, followed by responding emergency protection with failure of the rod AZ1

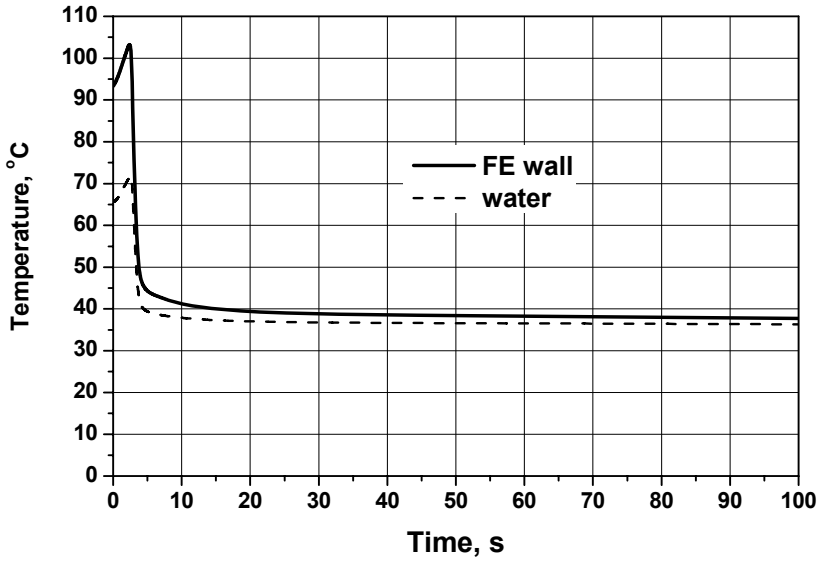

Figure 4. The maximum temperatures of the FE surface and the core outlet coolant versus time

For fresh core, values of K_{eff}, the fuel burnup level and the reactor operation cycle are calculated in course of step-by-step replacement of the water reflector by the beryllium one. In table 3 the FAs with the highest burnup are marked. With 24 beryllium blocks loaded to the core, the 50-% maximum burnup level is reached in the central core cell (6-5).

Table 3. Burnup and Power Generated in the core FAs
in course of step-by-step loading blocks of beryllium reflector to the core

Core	«16+10»		«16+10»+10Be (1-st charge)		«16+10»+17Be (2 charge)		«16+10»+24Be (3 charge)		16+10+34Be (4 charge)		«16+10»+52Be (5 charge)	
Cycle	1		2		3		4		5		6	
Cell	Burn.,%	P, kW	Burn.,%	P, kW	Burn.,%	P, kW	Burn.,%	P, kW	Burn.,%	P, kW	Burn.,%	P, kW
3–4 AP	10.7	194.0	23.8	200.2	31.4	215.1	38.4	201.0	41.8	203.4	43.5	204.6
4–3 KO11	10.3	188.4	22.7	186.7	29.5	194.2	36.4	199.5	39.7	194.2	41.4	202.5
4–6 KO12	11.5	211.3	25.2	208.5	32.9	219.8	40.0	205.9	43.4	206.6	45.1	202.5
6–3 KO21	11.5	209.3	24.2	195.3	30.8	190.6	38.0	208.5	41.4	200.6	43.1	206.1
7–8 KO22	10.4	190.4	23.1	192.5	29.8	190.8	36.8	201.9	40.2	203.6	42.1	216.8
8–3 KO31	10.7	194.6	23.3	194.0	29.9	187.7	36.9	205.7	40.4	201.7	42.2	211.9
8–6 KO32	11.7	213.0	26.1	222.1	33.5	212.6	40.5	208.3	44.0	210.0	45.7	206.4
7-3 AZ1	10.9	199.9	23.3	189.5	29.9	184.2	37.1	209.4	40.6	202.1	42.5	222.6
5–8AZ3	9.7	178.0	21.6	182.4	28.3	189.9	35.0	194.0	38.2	187.7	40.0	204.4
9–4 AZ2	10.3	187.7	23.8	204.2	30.8	200.4	37.6	197.6	41.0	198.5	42.7	202.3
9–5	8.3	188.5	19.9	221.6	25.9	214.4	31.8	211.7	34.8	223.5	36.4	223.0
4–4	10.7	243.3	23.0	239.0	29.7	240.4	36.3	245.4	39.6	235.3	41.1	233.6
4–5	10.4	235.5	22.7	236.6	29.6	250.7	36.3	243.0	39.5	238.0	41.0	229.2
5–4	11.0	250.7	24.1	251.6	31.4	265.5	38.2	248.1	41.5	246.1	43.1	235.8
5–6	13.2	301.5	28.2	286.5	36.2	290.6	43.6	273.4	47.1	264.3	48.7	252.4
5–7	10.1	231.3	22.2	232.0	29.0	244.7	35.5	239.0	38.7	232.7	40.2	228.2
6–4	13.8	315.6	28.9	294.1	36.7	281.7	44.2	278.4	47.8	268.6	**49.4**	**259.8**
6–5	**15.7**	**360.7**	**33.0**	**331.1**	**41.7**	**317.8**	**49.7**	**296.8**	**48.2**	**301.8**	**50.1**	**287.5**
6–7	10.0	228.7	22.2	232.1	28.7	234.4	35.3	237.6	38.5	234.7	40.1	234.1
7–4	10.9	250.0	23.5	242.6	30.0	235.9	36.8	250.2	40.1	245.7	41.7	239.2
7–6	13.3	304.4	28.9	302.5	36.8	287.5	44.2	271.5	41.0	285.1	42.8	271.7
7–7	10.9	248.5	24.0	253.1	30.9	248.3	37.7	246.6	41.0	246.4	42.6	241.4
8–4	10.7	246.4	23.8	251.6	30.5	242.1	37.2	247.6	4.5	305.6	6.7	300.8
8–5	10.4	239.0	23.8	257.6	30.6	245.7	37.1	242.8	40.4	237.4	42.0	230.0
4–7	8.9	204.4	19.5	198.7	25.2	201.6	31.4	223.9	34.4	212.6	35.9	233.0
5–3	8.0	184.6	18.1	194.0	24.1	213.7	30.0	212.4	32.9	214.2	34.4	220.3
K_{eff}	1.0788		1.0803		1.0664		1.0677		1.0462		1.0645	
ρ %	7.33		7.43		6.23		6.34		4.40		6.06	
ρ_{EOCr} %	0.36		0.46		0.61		0.34		0.74		2.31	
Op.time, day	90		110		60		60		30		15	

Cartogram of the core loading with beryllium is presented in Fig. 5. Appropriate variation of reactivity over the reactor cycles is shown in Fig.6, related to Table 3. For the core last state, values of K_{eff}, fuel burnup and the reactor operation time at the afterburning mode with permutations and charges of fresh FAs are calculated (Table 4). The cells with removed fuel assemblies, burnt up to ~50%, are marked with red color.

Fig.7 demonstrates variation of reactivity versus the reactor operation cycles (figures correspond to charge numbers).

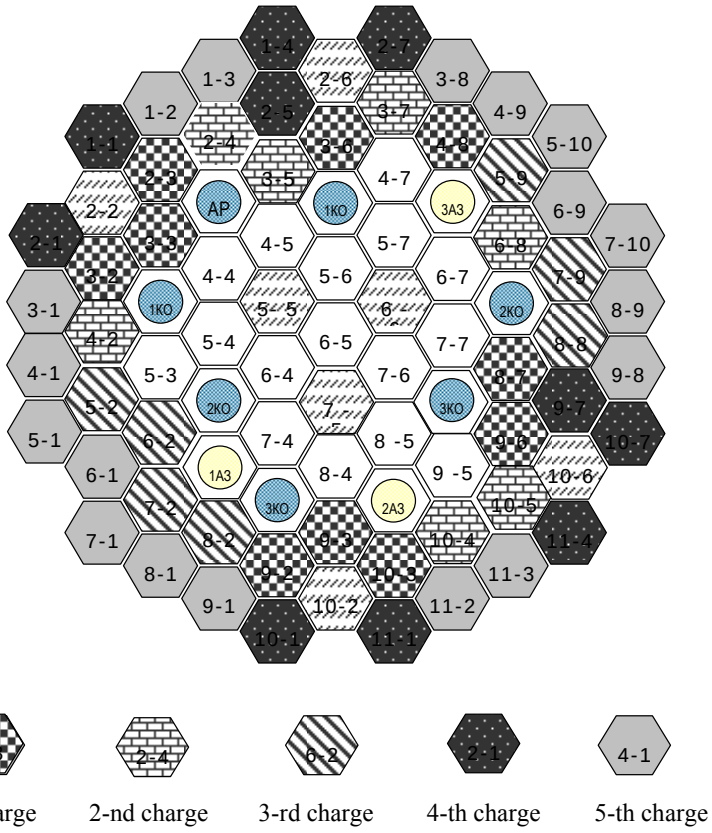

Figure 5. Cartogram of step-by-step loading pieces of beryllium reflector (52 blocks)

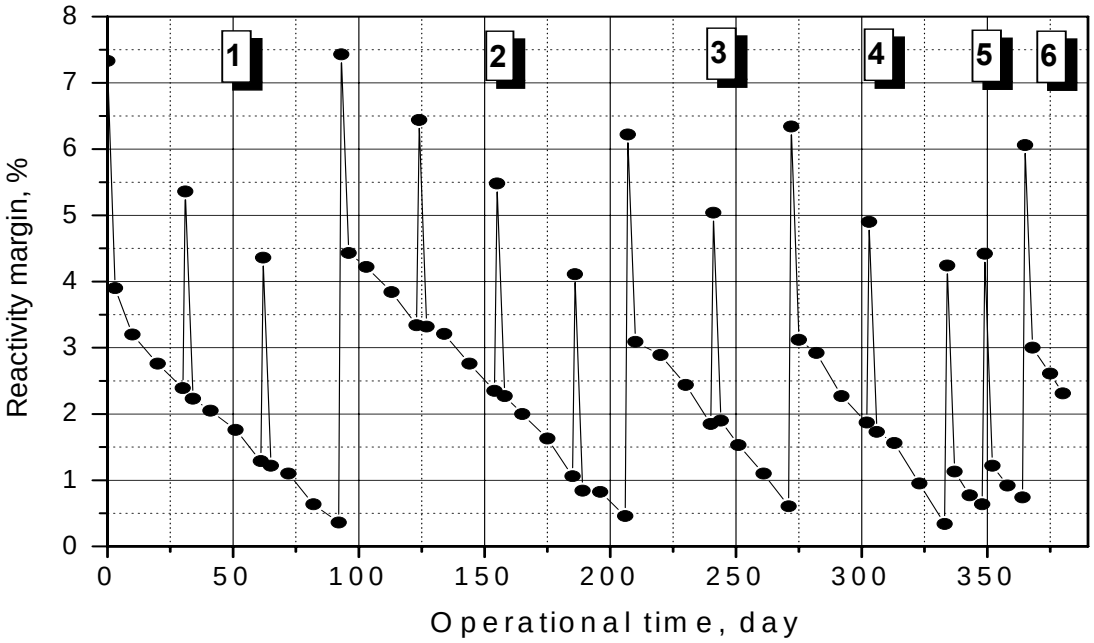

Figure 6. Reactor operation in course of replacement of water reflector by beryllium one (52 beryllium pieces) up to achieving the 50-% maximum average burnup

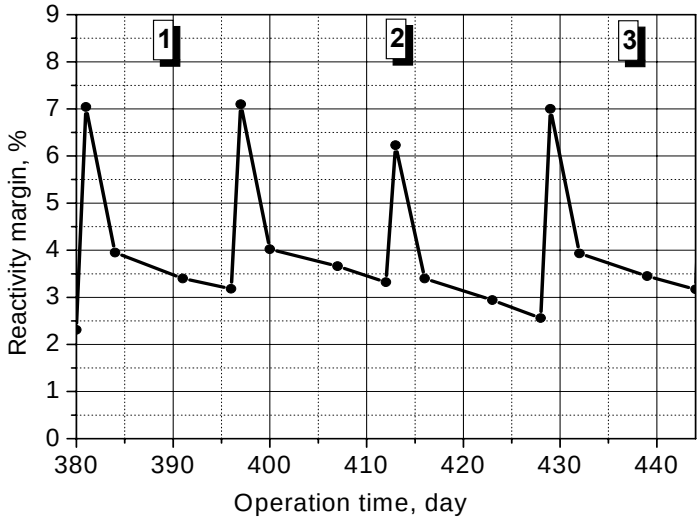

Figure 7. Reactor operation at the overburning mode to achieve the 50-% maximum average burnup with replacement of burnt FAs by fresh ones

Table 4. Burnup and Power Generated in FAs at the Afterburning Mode

Cell	Burnup, %	P, kW	Burnup, %	P, kW	Burnup, %	P, kW	Burnup, %	P, kW
	«16+10»+52Be		1-st overcharge		2-nd overcharge		3-rd overcharge	
3-4 AP	43.5	204.6	45.3	207.2	48.6	203.9	50.3	192.5
4-3 KO11	41.4	202.5	43.2	200.4	46.4	198.3	47.9	179.7
4-6 KO12	45.1	202.5	46.8	199.1	**50.0**	199.8	2.5	280.6
6-3 KO21	43.1	206.1	44.8	198.2	48.0	200.8	49.5	181.2
7-8 KO22	42.1	216.8	43.9	209.6	47.3	213.4	49.1	210.4
8-3 KO31	42.2	211.9	43.9	199.9	47.2	204.9	48.8	182.5
8-6 KO32	45.7	206.4	47.4	199.1	**50.6**	202.4	2.5	282.5
7-3 AZ1	42.5	222.6	44.3	210.8	47.7	214.0	49.3	191.4
5-8AZ3	40.0	204.4	41.7	201.5	45.0	202.6	46.7	200.6
9-4 AZ2	42.7	202.3	44.3	188.9	47.5	221.5	49.0	183.4
9-5	36.4	223.0	37.8	212.7	40.7	299.7	42.1	210.6
4-4	41.1	233.6	2.2	297.2	6.4	229.9	8.5	275.0
4-5	41.0	229.2	42.6	231.7	45.5	257.0	46.9	216.1
5-4	43.1	235.8	36.2	254.5	39.5	262.9	41.1	242.6
5-6	48.7	252.4	**50.4**	249.3	47.9	226.4	49.6	254.0
5–7	40.2	228.2	41.7	222.8	44.6	270.3	46.1	221.8
6-4	**49.4**	259.8	44.4	264.5	47.8	298.9	49.5	248.3
6–5	**50.1**	287.5	45.1	299.1	48.9	234.0	50.7	283.2
6-7	40.1	234.1	41.6	226.1	44.6	237.0	46.1	232.5
7– 4	41.7	239.2	43.2	228.6	46.2	341.1	47.6	214.6
7– 6	42.8	271.7	44.5	262.1	13.5	242.8	15.8	327.8
7– 7	42.6	241.4	42.7	234.9	45.8	312.5	47.3	235.9
8– 4	6.7	300.8	8.7	282.2	4.4	225.0	6.5	284.1
8–5	42.0	230.0	43.4	217.9	46.3	230.3	47.6	211.1
4-7	35.9	233.0	37.6	231.0	40.6	270.5	42.0	187.9
5-3	34.4	220.3	2.0	270.3	5.8	203.9	7.7	269.3
ρ, %	6.06		7.04		7.1		7.0	
ρ_{EOC} ,%	2.31		3.18		2.56		3.17	
Op.time, d.	15		15		2×15		15	

The 1-st charge: discharging the cell 6-4; permutations 7-6→6-4; 4-4→7-6; charging the cell 4-4; discharging the cell 6-5; permutations: 5-4→6-5; 5-3→5-4; charging the cell 5-3

The 2-nd charge: discharging the cell 5-6; permutations 7-6→ 5-6; 8-4→7-6; charging the cell 8-4

The 3-rd charge: FAs-2 in cells 4-6 and 8-6, with control rods KO12 and KO32, are replaced by fresh ones

Neutron flux densities in irradiation channels have been calculated for all states of the core. Table 5 demonstrates that the thermal neutron flux density in creases in all irradiation channels as water reflector is changed by beryllium one.

Table 5 – Neutron flux density in the core irradiation channels

Core	«16+10»	«16+10»+24Be	«16+10»+34Be	«16+10»+ 52Be
K_{eff}	1.0778(2)	1.0485(2)	1.0463(2)	1.0600 (2)
Cell	$E_n \leq 0.4$ eV / $E_n \geq 1.15$ MeV			
5-5	$2.1\cdot10^{14}$/ $3.8\cdot10^{13}$	$2.2\cdot10^{14}$/ $3.6\cdot10^{13}$	$2.2\cdot10^{14}$/ $3.7\cdot10^{13}$	$2.2\cdot10^{14}$/ $3.8\cdot10^{13}$
6–6	$2.1\cdot10^{14}$/ $3.7\cdot10^{13}$	$2.1\cdot10^{14}$/ $3.7\cdot10^{13}$	$2.2\cdot10^{14}$/ $3.8\cdot10^{13}$	$2.2\cdot10^{14}$/ $3.6\cdot10^{13}$
7–5	$2.2\cdot10^{14}$/ $4.1\cdot10^{13}$	$2.3\cdot10^{14}$/ $3.8\cdot10^{14}$	$2.3\cdot10^{14}$/ $3.9\cdot10^{13}$	$2.2\cdot10^{14}$/ $3.7\cdot10^{13}$
2–2	$5.4\cdot10^{13}$/ $4.0\cdot10^{12}$	$6.8\cdot10^{13}$/ $3.8\cdot10^{12}$	$8.5\cdot10^{13}$/ $4.3\cdot10^{12}$	$9.2\cdot10^{13}$/ $3.4\cdot10^{12}$
2–6	$4.5\cdot10^{13}$/ $3.3\cdot10^{12}$	$6.3\cdot10^{13}$/ $2.8\cdot10^{12}$	$8.1\cdot10^{13}$/ $3.5\cdot10^{12}$	$8.8\cdot10^{13}$/ $3.0\cdot10^{12}$
10–2	$5.7\cdot10^{13}$/ $3.8\cdot10^{12}$	$8.4\cdot10^{13}$/ $4.2\cdot10^{12}$	$9.1\cdot10^{13}$/ $4.7\cdot10^{12}$	$1.0\cdot10^{14}$/ $4.7\cdot10^{12}$
10–6	$4.7\cdot10^{13}$/ $3.0\cdot10^{12}$	$7.3\cdot10^{13}$/ $3.4\cdot10^{12}$	$8.6\cdot10^{13}$/ $3.3\cdot10^{12}$	$9.1\cdot10^{13}$/ $3.9\cdot10^{12}$
A	$6.8\cdot10^{11}$/ $4.6\cdot10^{10}$	$1.0\cdot10^{12}$/ $7.6\cdot10^{10}$	$1.0\cdot10^{12}$/ -	$1.0\cdot10^{12}$/ -
B	$3.3\cdot10^{12}$/ $2.0\cdot10^{11}$	$3.0\cdot10^{12}$/ $4.0\cdot10^{11}$	$4.0\cdot10^{12}$/ $3.5\cdot10^{11}$	$6.0\cdot10^{12}$/ $2.8\cdot10^{11}$

Remark: Banks in table mean that in these cases values of the neutron flux are small, being beyond of sensitivity of the calculation technique.
A and B – experimental channels in the reactor vessel, having diameter 200 and 100 mm respectively.

CONCLUSIONS

1. Among variety of FAs with low-enriched fuel considered, the FA with tube FEs, 1.6 mm thick, has been chosen. Fuel is uranium dioxide dispersed in aluminum matrix, uranium density is 2.8 $g\cdot cm^{-3}$. FA-1 and FA-2 (housing CPS control rods) contain eight and five FEs respectively. The design chosen makes it possible to increase the mass of U-235 per FA up to 252.6 g, against 111.0 g in the existing one. The FA well-developed heat removal surface makes it possible to create a compact core with high neutron flux density in irradiation channels.

2. The initial fresh core, composed of 16 eight-tube FAs and 10 five-tube ones, was determined; its reactivity margin comprises 7.2%Δk/k.
3. The net efficiency of shim elements (KO) and the automate rod (AP), 2.7% Δk/k, makes it possible to get rid of emergency caused by spontaneous introduction of positive reactivity [spontaneous withdrawal of the most efficient shim element (KO) followed by fault of the most efficient protection rod (AZ)]. The net worth of the control rods KO and AP, in a case of the core beryllium reflector is ~12%Δk/k, of the protection rods AZ - 4.2% Δk/k.
4. Via calculations, a procedure of gradual replacement of the water reflector by the effective beryllium one has been determined. The reactor operation cycle for this procedure comprises 365 days, and, as a result, the 50% maximum burnup is reached in three FAs.
5. The thermal neutron flux density in central channels comprises $2.1 \div 2.2 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$, whereas in peripheral ones, depending on reflector material - up to $5 \cdot 10^{13}$ $cm^{-2} \cdot s^{-1}$.

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