THE FUEL CYCLE OF REACTOR PIK [*)]

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ABSTRACT

A neutron feasibility study for HEU (90%)-MEU (36%) conversion of the reactor PIK was performed. The weak absorbing aluminum matrix was proposed in meat of the new PIK-2 FE instead of copper in reference case of standard PIK. The stainless steel cladding was left the same. For the additional gain in reactivity the stainless steel vessel and housing were changed for aluminum ones. The neutronics of the full scale computer model of PIK reactor core was computed with Russian Monte Carlo code MCU PR. Calculations show that a uranium density of 3.64 gU/cm^3 of MEU (36%) fuel leads to better core parameters. Compared to reference case, the PIK-2 FE with MEU fuel and 1/3 lower loading by ^{235}U have a longer equilibrium fuel cycle (27 *fpd* instead of 24 *fpd*) and higher burnup (37.3% instead of 23.7%). Due to lower neutron absorption in aluminum vessel and housing, all thermal neutron fluxes in D_2O-reflector increased about 1.4 times. The worth of control regulators increased several times. This neutronic feasibility study of fuel enrichment reduction of PIK reactor is sufficient to start the fabrication feasibility study and subsequent in-pile irradiation tests of PIK-2 FE with MEU (36%) fuel.

1. INTRODUCTION

1.1. Design of the reactor. The high-flux research nuclear reactor PIK is under construction south of St. Petersburg and 4 km from the town of Gatchina [1-2]. The purpose of this reactor is the study of fundamental properties of matter, investigations of new materials as well as radiobiological and applied research. The reactor is equipped with sources of hot, cold and ultracold neutrons. The design and parameters of reactor PIK were chosen such as to yield the maximum productivity of events in the experimental equipment. At the same time, realistic technological and heat transfer limitations were taken into account. As a result, the chosen conceptual design was that of a reactor with a compact light water core, water trap and heavy water reflector.

Reactor PIK will be the most powerful research reactor in the world (P=100MW) with highest thermal neutron flux in the water trap ($4.5\cdot10^{15}$ n/cm^{2}s) and D_2O-reflector (above 10^{15}n/cm^{2}s). The reactor core is contained in a cylindrical steel vessel 12X18H10T (ø406mm×8mm), enclosed by its housing (ø 420mm×3mm) and surrounded by a heavy water tank of about 2 m height and 240 cm diameter (Figs.1, 2). The 4 mm gap between vessel and housing is filled with heavy water for vessel cooling. The tank is surrounded by a iron-water and concrete biological shield. A cylindrical light water trap of 104 mm diameter is formed inside the guide after extraction of the absorbing shutters. The external size of the guide hexagon is 115 mm. Inside the guide are the central controls: two hafnium shutters (ø98mm×6mm) of density 13.1 gHf/cm^3, without the coating. The absorbing shutters move in opposite directions from the central plane of the core, forming a window ΔH between the absorbing hafnium sheets. When the shutters are closed ΔH=1.2 cm; when they are completely open ΔH=61.2 cm. The 18 fuel

assemblies (FA) are placed on a supporting lattice between the guide and casing. Twelve of them have an irregular hexagonal shape and contain 241 fuel elements (FE's) and six displacers each (Fig.2). Each one of the remaining six FA's

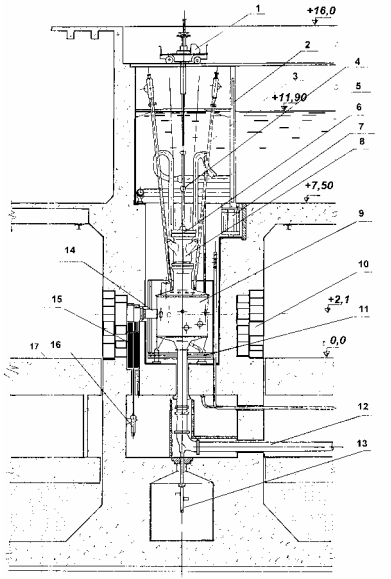

Fig.1. Lateral cut of the PIK reactor[2]. 1. Refueling machine; 2. Isolating door; 3. Channel of CR; 4. CEC; 5. Inlet cooling pipe; 6. Lid; 7. Fuel transfer drum; 8. Upper vessel; 9. D_2O tank; 10. Biological shielding; 11. Iron-water shielding; 12. Outlet cooling pipe; 13. Driver of the shutter; 14. Horizontal channel; 15. Shield plug; 16. Driver of the plug. 17. Protected against vibration floor.

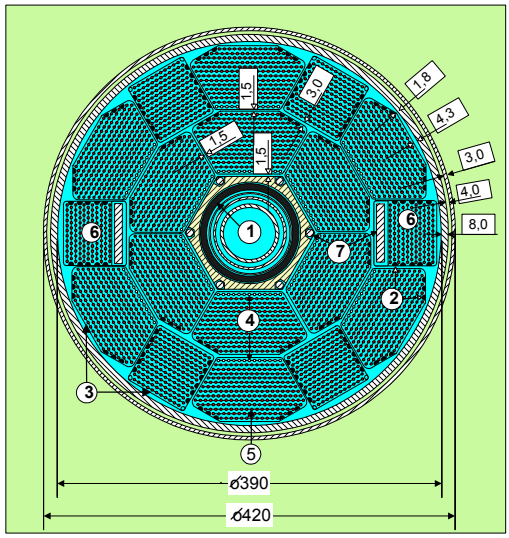

Fig.2. Transverse cut of the core [2]. 1.Shutter (Hf); 2. Burnable absorption rod (Gd_2O_3+ZrO_2); 3. Zirconium housing of FA; 4. Fuel elements with 0.48 of standard uranium contents; 5. Fuel elements with standard uranium contents; 6. Fuel assembly for irradiation tests; 7. Irradiation samples. (The dimensions are in mm.)

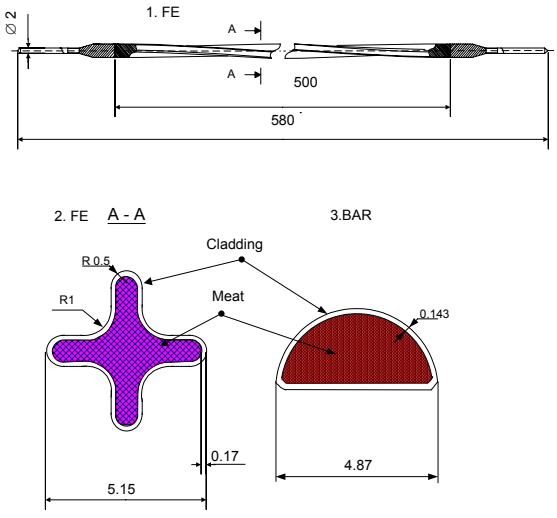

Fig.3. FE and BAR of PIK reactor [2]. (The dimensions are in mm.)

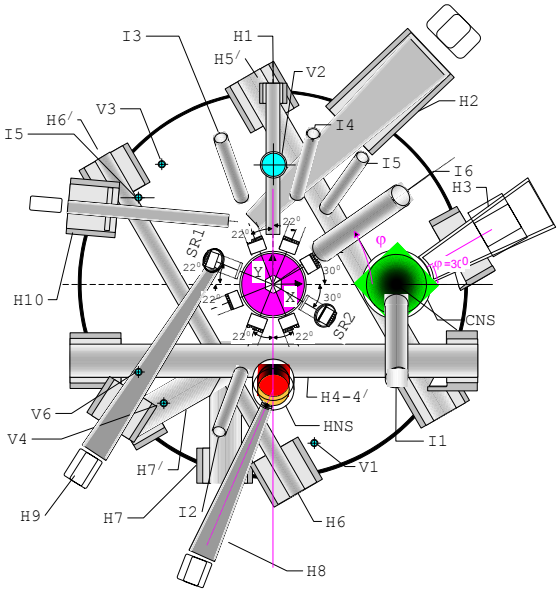

Fig.4. Scheme of experimental channels [2]. (Top view.)

of square cross section contains 161 FE's and 14 displacers. The displacers are at the same time burnable absorbers (BAR's) Fig.3. The spacing of the triangular lattice is a=5.23 mm. The total number of FE's in the core is 3858. The FE's are cross-shaped in cross section. The geometrical sizes of FE's are shown in Fig.3. The length of the fuel layer is 500 mm. To ensure correct distancing, the FE edges are of helical shape with a pitch of 30 cm.

The geometry dimensions of the standard PIK FE are listed in the first column of the Table 1 [2]. The reactor fuel enrichment was 90%. To reduce the non-uniformity of heat transfer in the first FE layer next to the trap, the fuel in the hexagonal FA is profiled and is 0.48 of the nominal. It is assumed that the uranium contains 1% of isotope ^{234}U [3]. The 8 equal outer control rods are placed in the reflector tank. The rods are inserted in inclined channels at an angle of 8^o to the vertical. Two rods are used as safety rods (SR) and 6 rods are under manual control. Ten horizontal experimental channels, 6 inclined channels and 6 vertical channels are placed inside the reactor tank (Fig.4). The materials, of which they are made, their sizes and coordinates are given in Ref.[2]. The composition of alloys is given in Ref.[2]. The volume of heavy water in the tank is about 8.5 m^3. The concentration of heavy water is (99.86 ±0.03)%. A source of cold neutrons (CNS) and of hot neutrons (HNS) are also located in the reflector.

Table 1. Standard PIK and PIK-2 FE specification (lattice spacing a=5.23 mm; cell area $S_c = \sqrt{3}a^2/2 = 23.67\text{mm}^2$; $V_c = 11.84\text{cm}^2$; cell water ratio $\omega_{H_2O} = 0.575$; meat ratio $\omega_M = 0.305$)

		Standard PIK	PIK-2	
1	Meat	UO_2+Cu	UO_2+Al	
2	^{235}U enrichment, ζ_5, w.%	90	90	36
3	UO_2 volume fraction, w.%	25	15	37.7
4	U meat density, γ_U^M, g/cm^3	2.194	1.317	3.640
5	^{235}U meat density, g/cm^3	1.967	1.185	1.311
6	$\gamma_5 = \gamma_U^M \omega_M \zeta_5$, g^{235}U/$l$	600	360	400
7	Matrix material density in meat, g/cm^3 [1)]	6.25	2.27	1.53
8	K_∞	1.6176(3)	1.7420(3)	1.6141(5)
	ρ_∞ %	38.18(1)	42.59(1)	38.43(2)

[1)] The porosity was taken into account [9].

1.2. Methods of Calculation. The main part of calculations in this report was performed with a new Russian Monte Carlo code MCU PR [4]. The code is designed for calculation of reactor neutronics. In the new version compared to the old one the constants library is significantly expanded. In the new version of library DLC/MCUDAT2.1 the number of nuclides is increased to 285. It is possible to calculate the change of fission fragments and of the burnable absorber isotopes during the reactor cycle. All calculations were done only heterogeneously. For all FE's we have separately considered the meat, cladding, water and the FA casing. To find the accuracy of our reactor PIK calculations special experiments were performed at the PIK Mock-up. The Mock-up is a critical assembly which represents a complete model of the core and reflector of reactor PIK [5]. Six series of measurements of Mock-up poisoning with boric acid of various concentrations were carried out in 1987 for comparison with calculations. The set of 60 critical measurements differ by boron poisoning of light water and by the positions of the central control shutters. In two series the outer reflector was light water, in four others it was heavy water. The results of comparison of reactivity calculations with data of poisoning experiments are

summarized in Ref.[6]. For 56 experimental points the calculated reactivity deviation from zero is 0.1-0.2%. Code MCNP-4B with ENDF/BVI library gives similar results. Thus the comparison with data of the boron poisoning calculations for the Mock-up with heavy-water reflector demonstrate that code MCU PR can be recommended for calculations of the operating modes of reactor PIK.

2. NEW ALUMINUM BASED PIK-2 FE

2.1. New PIK-2 FE composition. The standard PIK FE withstand large non-uniformities of energy release thanks to the good heat conduction of the bronze matrix. However the PIK-type meat have at least two shortcomings. First, the copper of bronze strongly absorbes neutrons and reduces the reactor's multiplication factor. Second, in order to achieve a sufficiently high multiplication factor one needs a high uranium concentration γ_5 in the core. The way out is to use weakly absorbing structural materials, such as aluminum. As a material for the heat transport in the meat matrix, aluminum is second after copper.

Concerning the FE cladding, one can advance three considerations in favour of continuing to use stainless steel: 1. The strength of steel is twice that of aluminum alloys. Aluminum cladding has to be of approximately twice the thickness of steel cladding in order to contain fragments equally well. 2. At high water velocities and large heat loads, corrosion causes an oxide film to form on the aluminum surface, which has poor thermal conduction. Without a careful study of this phenomenon one cannot recommend aluminum cladding for high-flux reactor FE's. 3. An important argument in favour of steel FE cladding is the simplicity and reliability of its manufacturing technology: vibratorial compaction [7]. Thus we come to the conclusion, that the FE of reactor PIK with HEU and MEU fuel must contain an aluminum matrix and a steel cladding.

2.2. Reduction of uranium concentration in meat [8]. To establish the optimal content of fuel in the meat, we have considered the dependence of the multiplication factor K_∞ on the ^{235}U mean density γ_5 in the cell. We considered a triangular infinite lattice of infinitely long PIK fuel elements of pitch a = 5.23 mm. The curve for the copper meat grows without saturation. The curve for aluminum meat has a broad maximum at $\gamma_5 = 550\text{g}^{235}\text{U}/l$. Thanks to the presence of the plateau, the curve for the aluminum FE's of reactor PIK is practically unchanged under a reduction of γ_5 by 60% of the value for the standard FE's. There arises the interesting possibility to reduce the content of fuel in the FE's and to economise thereby annually cost of tens of kilograms of highly enriched uranium.

2.3. PIK-2 FE with MEU (36%) fuel. For MEU (36%) fuel we choose the meat with (UO_2+Al) ceramic in Al matrix and exactly the same as PIK-2 HEU geometry. In Table 1, the volume densities of UO_2 and of Al for $\gamma_5 = 400\text{g}^{235}U/l$ are listed. The multiplication factors for the infinite lattice of infinite PIK-2 MEU FE with MEU (36 w.%) fuel depending on γ_5 has a broad maximum at $\gamma_5 = 400\text{g}^{235}U/l$. The new PIK-2 MEU FE's with MEU (36%) fuel must be fabricated and tested by various in-pile irradiations. Only thereupon can we recomend the PIK-2 MEU FE for practical use.

3. FRESH CORE

3.1. Fresh core design. We have studied the cores with standard PIK FE and with aluminum based new PIK-2 FE. To gain in reactivity we exchange the cylindrical stainless steel vessel and housing for aluminum ones [10]. The aluminum vessel must be 10 mm thick; the aluminum housing can be 4 mm thick; the D_2O cooling gap remains 4 mm. Other wise the design of reactor PIK remains the same.

3.2. Contribution to reactivity of the fresh core components is shown in Table 2. The initial reactivity excess for the core with PIK-2 FE with HEU (90%) and MEU (36%) fuel is much higher at lower concentrations of ^{235}U compared to the reference case of standard PIK FE. The worth of 144 BAR's is about 2 times higher; the worth of shutters is nearly the same. Due to the change of the steel of vessel and housing for aluminum, the worth of 8 control rods significantly increased (about 3.6 times). Contribution of all experimental facilities to reactivity by replacing with heavy water is small: 0.4(1)% for reference case and 1.0(1) for aluminum vessel and housing and PIK-2 FE with MEU fuel. The reactivity loss due to fuel profiling is higher in the reference case: –1.0(1) compared to –0.53(1) for case of MEU fuel.

Table 2. Contribution to K_{eff} and reactivity the fresh core components.

		Standard PIK	New core	
	Vessel and housing	Stainless steel	Aluminum	
	FE type	PIK	PIK-2	
	Meat	UO_2+Cu	UO_2+Al	
	Fuel	HEU (90%)	HEU (90%)	MEU (36%)
	γ_5, g $^{235}U/l$	600	360	400
1	Core with trap components, Exp.Fac., fuel profiled, $\Delta\rho$, %	1.1415(5) 12.40(4)	1.2371(5) 19.17(3)	1.1890 15.90(4)
2	With 144 BAR's, $\Delta\rho_{BAR's}$, %	1.1061(4) –2.80(5)	1.1579(5) –5.53(5)	1.1195(5) –5.22(5)
3	Shutters dropped ΔH=1.2cm, $\Delta\rho_{Sh}$, %	1.0215(5) –7.49(6)	1.0700(5) –7.09(6)	1.0345(5) –7.34(6)
4	Shutters +6RR+2SR $\Delta\rho_{8CR}$, %	1.0035(6) –1.76(8)	1.0048(5) –6.06(7)	0.9705(5) –6.37(7)
5	Equilibrium fuel cycle, *fpd*	24	32	27

3.3. Neutron fluxes for fresh cores are shown in Table 3. Due to absence of strongly absorbing steel the thermal neutron fluxes in the D_2O-reflector are about 1.4 times higher. For the dropped shutter the perturbed thermal flux in the center of the horizontal channel with diameter 8.2 cm is increased up to $\Phi_{th} = 1.4 \cdot 10^{15}$ n/cm^{2}s.

Table 3. Thermal (E<0.625 eV) Φ_{th} and fast (E>0.8 MeV) Φ_F neutron fluxes. Regulating rods and shutters are withdrawn.

	Vessel and housing	Steel		Aluminum			
	FE type	PIK HEU (90%)		PIK-2 HEU (90%)		PIK-2 MEU (36%)	
	γ_5, g$^{235}U/l$	600		360		400	
	Reactivity excess, $\Delta\rho\uparrow$, %	9.59(3)		13.64(4)		10.67(4)	
	Φ_i, 10^{14} n/cm^{2}s	Φ_{th}	Φ_F	Φ_{th}	Φ_F	Φ_{th}	Φ_F
1	CEC in trap	45.6(6)	7.2(4)	43.7(8)	7.5(1)	42.1(8)	7.3(7)
2	Core center	1.68(5)	12.5(2)	2.7(1)	12.4(2)	2.3(1)	11.9(2)
3	Vessel	3.94(2)	5.47(2)	9.9(1)	6.15(4)	9.20(6)	6.01(4)
4	Horizontal channel H4-4', D=8.2 cm	9.47(7)	0.14(1)	13.1(1)	0.16(1)	12.9(1)	0.18(1)
5	Radial channel H1	6.3(1)	0.24(1)	8.9(2)	0.28(2)	8.5(2)	0.32(2)
6	Inclined channel I6	5.31(4)	0.15(1)	7.3(1)	0.19(1)	6.9(1)	0.18(1)

4. EQUILIBRIUM FUEL CYCLE

As an equilibrium cycle of reactor PIK we have considered a cycle with reloading of one half of the core. Six burnt-up peripheral hexagonal fuel assemblies (FA) are moved in, and three burnt-up square FA's are replaced by fresh ones. Six hexagonal and three square FA's are off-loaded from the center of the core. All FA's contain gadolinium burnable absorption rods (BAR's). In this case the controls overcompensate the positive reactivity at the beginning of the cycle (HEU and MEU fuel case) with surplus required by the rules of the Regulatory Commission. This was the working regime chosen as the Reference Case.

4.1. Beginning of the equilibrium cycle. For the Reference Case the average burnup of fuel (^{235}U) is 6% over the entire core at the beginning of the equilibrium cycle (BOEC) for HEU fuel. The reactor becomes critical for the following settings of the controls: a shutter gap of ΔH=7.2 cm, 6 control rods in the heavy-water reflector completely lowered (to a level of Z= –25 cm with respect of the core center), and two safety control rods SR-1 and SR-2 in the upper withdrawn position. For the MEU fuel the average burnup of fuel at BOEC is higher (11%). The shutter window is the same, but only two of control rods are completely lowered.

4.2. Initial reactivity excess. The reactivity excess for the shutters at the beginning of the reactor cycle (relative to the inserted shutter with window to ΔH=1.2 cm) is about –1.0% for both cases (HEU-MEU). The worth of the safety control rods SR-1 and SR-2 is $\Delta\rho^0_{az} = -0.50(10)\%$ for HEU case and –1.87(9)% for MEU case. In both cases it is enough to fulfill the shutdown margin requirements. The total worth of the shutters relative to their initial position (ΔH=7.2 cm) and of the 6 control rods is $\Delta\rho^0_{tot} = -7.38(10)\%$ for HEU case. For the case of MEU fuel the worth of shutter with 2 control rods is –7.66(9)%. The gadolinium absorbers have a worth only in 9 fresh outer FA's (72 BAR's). Their worth is $\Delta\rho^0_{Gd} = -1.70(10)\%$ in the HEU case and sufficiently greater for the MEU case –3.83(6)%. Altogether we have about 2.41% greater reactivity excess for the case of MEU then HEU at BOEC.

4.3. Core geometry. To perform the reactor cycle calculation we have divided the core of reactor PIK into zones such that the nonuniformity coefficient of energy release K_v changed within each zone by no more than 0.5. Vertically the core was divided into 5 zones: upward from the core

center they had heights of 3, 12 and 10 cm, respectively, and symmetrically downwards. Zones symmetrical to the central plane were considered together. The cross-shaped fuel elements in the FA's were described heterogeneous. Treated separately were the 1st and 2nd layers of FE's and the combined region containing the 3rd and 4th FE layers adjacent to the central trap in the inner hexagonal FA's (see Fig. 2). The fuel in the first FE layer was profiled to a level of 48% in all of the twelve hexagonal FA's. The BAR's had the shape of semi-cylinders of zirconium, the poisoner of the same shape consisted of a Gd_2O_3+Y_2O_3+ZrO_2 mixture. The poisoner was divided radially into 4 physical zones to emulate different burnup rates of the external and internal layers.

4.4. Method of calculation of the fuel burnup during the reactor cycle. In calculating the build up of fission products and the poisoning by them, we have separately considered the strong absorbers ^{135}Xe, ^{149,151}Sm, ^{148,148m}Pm, ^{155}Eu, ^{113}Gd, and ^{157}Gd, some moderate absorbers: ^{147}Pm, ^{133}Cs, ^{131}Xe, ^{143,145}Nd, and ^{103}Rh, and other nuclides of the decay chains of these nuclei. The moderate and weak unstable absorbers were merged into an effective short-lived (lifetime 5 days) pseudo-fission product U5T2. The total cumulative yield of nuclides in this product was 44.5%. The energy dependence of cross sections of this product was obtained by averaging of the cross sections of the component nuclides, weighted with their cumulative yields and lifetimes. The resulting thermal cross section of the product was 237 b.

Similar we considered all weak absorbers merged into a second (stable) pseudo-fission product U5T1. The thermal cross section of this product is 5.03 b, the total cumulative yield is 146.7%. The calculation of the transmutations in the course of the reactor cycle was performed using program BURNUP[11], which is connected with program MCU PR [4].

The concentrations of 26 nuclides – fission products, and the concentrations of 6 pseudo-fission products (fission products of ^{235}U, ^{238}U and ^{239}Pu) were explicitly traced in the course of the calculations. For fission product nuclides the (n, γ) reactions and the decays into radioactive nuclei were taken into account. The lifetimes and branching ratios of radioactive nuclei were taken from Ref. [12]. The probabilities of formation of isomers in radiative capture reactions for thermal neutrons were taken from Ref. [13]. For actinides we have taken account of (n, γ) fission reactions and, where important, of (n, 2n) and (n, 3n). The data on the spectrum of fission product yields of uranium and plutonium was taken from library ENDF/BVI. As an additional condition we have assumed that the power of the reactor was constant and equal to 100 MW.

The cross sections σ_f, σ_a of all isotopes depend on the neutron spectrum, which varies with the changing isotopic composition. Therefore the differential equations describing the atomic density changes with time are solved in time steps, recalculating all functionals entering the system of equations. In this way the concentration of nuclides was predicted for an interval of time Δt of running reactor. The first interval Δt was chosen to be one day, the second interval was four days, and the further intervals were of 5 days duration. The length of the last interval was defined by the condition of stopping of the reactor due to lack of reactivity (with completely withdrawn shutters and control rods).

4.5. Main absorbers of reactor PIK. The rate of fuel burnup in reactor PIK is 1.34 g^{235}U/MW·days for HEU fuel and is 1.31 g^{235}U/MW·days for MEU fuel. (The initial load is 27.146 kg ^{235}U for fresh HEU fuel and 18.086 kg^{235}U for fresh MEU fuel.) The rate of reactivity loss of the reactor on the linear section is $d\rho/dt = -0.23(1)\%/\text{day}$ for the HEU case and $d\rho/dt = -0.30(1)\%/\text{day}$ for the MEU case. The reactivity loss is slightly higher for the MEU case due to lower ^{235}U load.

The mass of ^{239}Pu in the discharged FE's is 46 g for the equilibrium HEU fuel cycle, and the mass of ^{240}Pu is 4.9 g. For the equilibrium MEU fuel cycle the mass of ^{239}Pu in the discharged FE's is 187 g, and the mass of ^{240}Pu is 29g. At the end of the reactor HEU fuel cycle, the absorption of ^{238}U is 1.22% of the total, and those of ^{234}U and ^{240}Pu are 0.39% and 0.11%, respectively. For the MEU cycle the absorption of ^{238}U raised up to 5.52% and the absorption of ^{234}U and ^{240}Pu are 0.26% and 0.65%, respectively.

The main structural materials absorbers of reactor PIK in the HEU case are: Fe-13.3%, H-6.64%, Cu-5.94%, Cr-4.14%, Ni-3.15%, Al-1.85%, Mn-1.28%. It is Fe-9.89%, H-9.97%, Al-5.03%, Cr-3.07%, Ni-2.51% in the MEU case. This is due to changing of steel case to aluminum one and change of Cu in the fuel meat to Al in the MEU case.

4.6. Poisoning of the reactor. The total and relative contributions of the main poisoning elements ^{135}Xe and ^{149}Sm to the absorption at the end of the reactor cycle are shown in Table 4. The contribution of ^{135}Xe is 2.44%, that of ^{149}Sm is 0.522% in the HEU case and 2.57% , 0.553% respectively for the case of MEU.

Other important absorbers at EOEC are the stable pseudo-fission product U5T1 (0.81%-HEU, 0.96%-MEU) and the short-lived pseudo-fission product U5T2 (0.49%-HEU, 0.63%-MEU). The total contribution of other fuel burnup products to the absorption is of 1.31% (HEU) and 1.82% (MEU).

At EOEC the BAR's burn up totally in HEU and MEU cases. For the HEU case the total reactivity loss due to burn up of fuel and BAR's is $\Delta\rho_B(EOEC) = -3.7(1)\%$ and is –4.5(1)% for the MEU case. The total loss due to "Sm+Xe" is $\Delta\rho_{Xe+Sm}(EOEC) = -5.1(1)\%$ for HEU fuel and –5.4(1)% for MEU fuel. At EOEC the total reactivity excess is zero within the error bars: $\Delta\rho_t = 0.04(7)\%$ for the HEU case and we have small reactivity excess (0.39(6)%) for the MEU case.

Table 4. HEU (90%) and MEU(36%) fuel burnup and poisoning.

		HEU (Burnup of discharged fuel is 23.7%)			
		BOEC ($\bar{y}_F = 6\%$)		EOEC ($\bar{y}_F = 18\%$)	
		ρ_i, %	$\Delta\rho_i$, % [1)]	ρ_i, %	$\Delta\rho_i$, %
1	Fuel and BAR's burnup	8.92(7)	–0.67(8)	5.15(7)	–3.95(10)
2	Sm poisoning	7.62(7)	–1.30(9)	4.03(7)	–1.12(10)
3	^{135}Xe poisoning	–	–	0.04(7)	–3.99(10)
		MEU (Burnup of discharged fuel is 37.3%)			
		BOEC($\bar{y}_F = 11\%$)		EOEC($\bar{y}_F = 29.7\%$)	
		ρ_i, %	$\Delta\rho_i$, % [2)]	ρ_i, %	$\Delta\rho_i$, %
1	Fuel and BAR's burnup	9.29(7)	–1.38(8)	5.83(5)	–3.85(9)
2	Sm poisoning	7.76(7)	–1.53(9)	4.69(5)	–1.14(8)
3	^{135}Xe poisoning	–	–	0.39(6)	–4.30(9)

[1)] $\Delta\rho_i = \rho_i - \rho_{i-1}$; $\rho_0 = 9.59(3)$ for the fresh core with 144 BAR's (HEU), Table 2.
[2)] $\Delta\rho_i = \rho_i - \rho_{i-1}$; $\rho_0 = 10.67(4)$ for the fresh core with 144 BAR's (MEU), Table 2.

4.7. Burnup of gadolinium BAR's. The main absorbing nuclides in the natural mixture of Gd nuclei are ^{155}Gd (14.80% content) and ^{157}Gd (15.65%). In addition to these the natural mixture of gadolinium isotopes contains the following nuclides which were also taken into account in the calculations: ^{152}Gd (0.2%), ^{154}Gd (2.18%), ^{156}Gd (20.47%), ^{158}Gd (24.84%) and ^{160}Gd (21.86%).

The transmutations of isotopes are determined mainly by radiative neutron capture and the transition of a given isotope into an isotope of a higher atomic number. For the nuclei ^{158}Gd and ^{160}Gd, in view of the instability of the resulting isotopes, the scheme of transmutations were more complicated:

$$^{158}\mathrm{Gd} \xrightarrow{(n,\gamma)} {}^{159}\mathrm{Gd} \xrightarrow{\beta^-} {}^{159}\mathrm{Tb} \xrightarrow{(n,\gamma)} {}^{160}\mathrm{Tb} \xrightarrow{\beta^-} {}^{160}\mathrm{Dy}\,,\ {}^{160}\mathrm{Gd} \xrightarrow{(n,\gamma)} {}^{161}\mathrm{Gd} \xrightarrow{\beta^-} {}^{161}\mathrm{Tb} \xrightarrow{\beta^-} {}^{161}\mathrm{Dy}\,.$$

The radius of the semi-cylinder of the BAR is 2.2 mm. The entire volume was divided into 4 layers of thickness 0.19, 0.2, 0.3 and 0.4 mm, beginning with the outer edge of the semi-cylinder. The first layer, which is located in the most intensive fluxes of thermal neutrons, burnt up with the highest rate. Similarly the second and third inner layers burn up about equally, but at a somewhat smaller rate. The inner part of BAR's burn up with the lowest rate. In Fig.5 the burn up of ^{155}Gd in poison rods for different layers is shown. The poisons burn up during about 15-20 days for HEU case and during about 10-15 days for MEU case.

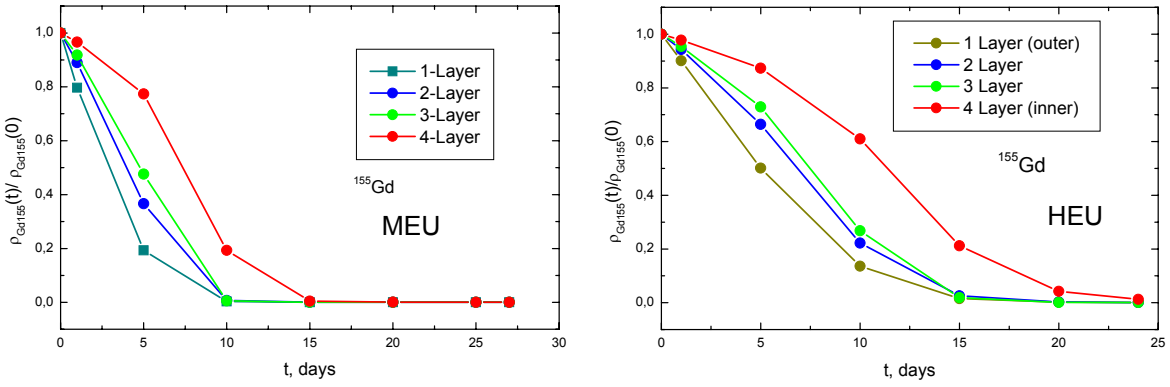

Fig.5. Temporal dynamic of the ^{155}Gd concentration changing in absorbers during reactor fuel cycle.

4.8. Dynamics of the control system. Within the first day of HEU fuel cycle operation of the reactor a negative reactivity of –3.25(10)% develops mainly on account of its poisoning. To compensate such a reactivity, six automatic control rods are completely withdrawn and the shutter window is increased to ΔH=15 cm. The further movement of the shutters during the reactor cycle (24 days) up to the moment when they are completely raised and the reactor is shut down, is shown in Fig. 6. After reactor shutdown for 7 days, during which the core is reloaded, the reactor starts up from the initial state, i.e. there is an equilibrium cycle of 31 days HEU. For the MEU fuel cycle 2 inserted control rods are also withdrawn and the shutter window is increased up to ΔH=14 cm at the end of the first day. The duration of the fuel cycle for the MEU case is 27 days with small access of reactivity at the EOEC, i.e. there is an equilibrium cycle of 34 days.

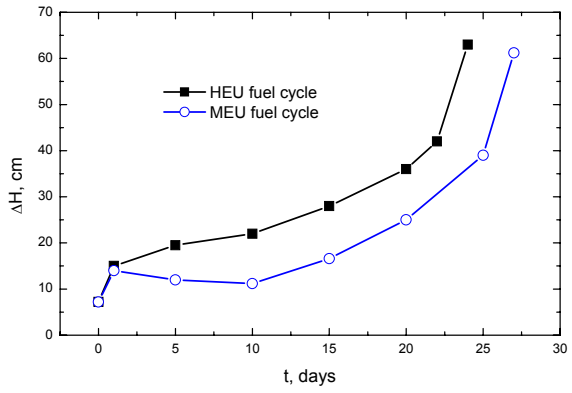

Fig.6. Shutter window temporal dynamics for the equilibrium HEU and MEU fuel cycles.

The mean burnup of fuel in the off-loaded FA's for HEU fuel is 23.65% and is increased to 37.27% for MEU fuel. The maximum burnup (62.23%-HEU, 72.03%-MEU) occurs in the central part of the first profiled layer of FE's The burnup of the second FE layer of the central part amounts to 42.82%-HEU and 56.82%-MEU. The maximum coefficient of nonuniformity of energy release arises in the second FE layer within the first day and is $K_V^{\max} = 2.86$ for the HEU fuel. It is lowered to 2.41 for the MEU fuel.

CONCLUSIONS

Calculations with Russian MCU PR code of full scale computer model of the PIK reactor in Gatchina show that the uranium density of 3.64 gU/cm^3 of MEU (36%) fuel in PIK-2 FE geometry gives better core neutronics than standard PIK FE with HEU (90%) fuel. Preliminary tested of Monte Carlo code MCU PR in calculations of PIK Mock-up boron poisoning experiments gave an accuracy in reactivity of (0.1-0.2)%. The PIK-2 FE with MEU (36%) in the same geometry as in reference case of standard PIK FE with HEU (90%) have (UO_2+Al) meat and same stainless steel cladding. For the additional reactivity gain the stainless steel of vessel and housing was changed for aluminum. The equilibrium fuel cycle was calculated for replacement of one half of the core. The MEU core containing 1/3 less ^{235}U fuel has a longer fuel cycle compared to the reference case (27 *fpd* instead of 24 *fpd*). With 7 days between two power runs the total fuel cycle is 34 days. By 9 run/year or 243 *fpd*/year we economize fuel for 2 standard HEU cores per year, or the cost of 54 kg^{235}U/year. Due to a weak absorbing vessel and housing all thermal fluxes in D_2O-reflector increase about 1.4 times. The worth of 8 control rods for a fresh core is 3.6 times higher compared to the reference case. The maximal volume coefficient of the energy release non-uniformity goes down and is equal to K_V=2.41.

The positive results of a neutronic feasibility study for HEU-MEU conversion of PIK reactor are sufficient to start the fabrication feasibility study of PIK-2 FE with MEU (36%) fuel. The fuel temperature in hot points must also be calculated. Serious R&D work is needed to show the feasibility of producing the FE with MEU fuel. In-pile irradiations in reactor WWR-M and SM-2 with post-examination tests are also needed. As to PIK-2 FE with LEU (19.75%) fuel, the composition of such FE is still not clear.

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