EPJ Nuclear Sci. Technol. **2**, 42 (2016)

DOI: 10.1051/epjn/2016035

EPJ Nuclear Sciences & Technologies

Available online at:
http://www.epj-n.org

REGULAR ARTICLE

The choice of the fuel assembly for VVER-1000 in a closed fuel cycle based on REMIX-technology

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Received: 21 May 2015 / Received in final form: 2 September 2016 / Accepted: 22 September 2016

Abstract. This paper shows basic features of different fuel assembly (FA) application for VVER-1000 in a closed fuel cycle based on REMIX-technology. This investigation shows how the change in the water–fuel ratio in the VVER FA affects on the fuel characteristics produced by REMIX technology during multiple recycling.

1 Introduction

There are several problems in the Russian nuclear energy sector: the huge quantity of accumulated spent nuclear fuel (SNF) and the limited inventory of cheap natural uranium for fuel fabrication. The solution of these problems leads to increase economic attractiveness of the nuclear industry. The main decision is in the implementation of a closed fuel cycle and recycling of the SNF. There is program which is based on the development of fast nuclear reactors in Russian Federation. This technology will have a significant contribution to the nuclear energy only in the distant future. The nuclear power plant fleet in Russia today is mainly based on the VVER reactors. It is important to perform the smooth transformation of the current nuclear system with implementation of thermal reactors in a closed fuel cycle. It will help to decrease the amount of SNF, reduce natural uranium consumption and improve reprocessing technologies.

There is experience of regenerated material implementation in the thermal reactors in the world based on the MOX-technology [1]. The main problem of MOX fuel usage is the degradation of Pu isotopic composition. The high level of Pu content in the fuel leads to limited (~30%) MOX fuel assemblies (FAs) loading in the core. The regenerated uranium (received in the reprocessing process) is stored or partly used for regenerated fuel fabrication. In Russia, the uranium separated from spent VVER-440 fuel is mixed with the uranium extracted from the spent BN-600 fuel and then used for fabricating RBMK-1000 fuel [1]. In this case, only regenerated uranium is used and plutonium is stored. The storage of regenerated Pu is very expensive.

In papers [2–4], it has been proposed to use in thermal reactors fuel made from unseparated mixtures of uranium and plutonium isotopes blended with enriched natural uranium. Such fuel is called as REMIX-fuel. Fuel fabrication technology is called REMIX-technology.

During reprocessing minor actinides and fission products (FPs) are removed. The main achievements of the REMIX-technology are simplified reprocessing process, natural uranium savings, multiple recycling and the possibility of full core loading. In papers [5,6], some new variants of the REMIX-fuel have been proposed, based on different feeding and fissile materials like ^{232}Th, ^{238}U, ^{233}U and ^{239}Pu. It has been shown that presence of constant feeding the fuel isotopic composition goes to an equilibrium state.

This paper shows the main features of the different FA concepts application in the VVER-1000 in a closed fuel cycle based on the REMIX-technology. FAs with different water to uranium volume ratios and three concepts of the REMIX-fuel were considered:

- water–fuel ratio changes in the range of 1.5–2.5 in the FAs (different FA variants);
- the fuel cycle is based on traditional REMIX-fuel with highly enriched uranium feeding, regenerated REMIX (MOX)-fuel with the reactor grade plutonium (RgPu) feeding or U–Th fuel (new REMIX(Th)) with ^{233}U feeding.

The reactor grade plutonium (RgPu) obtained by reprocessing of the SNF UO_2 from VVER-1000 with average burnup 49.3 MW d/kg$_{HM}$ and the average enrichment ~4.1 wt.%.

The basic attention in this paper focuses on the such results:

- the feeding material consumption (high-enriched uranium (HEU), RgPu and ^{233}U) during multiple recycling;
- the isotopic composition behavior (plutonium composition) during multiple recycling.

This values influence on the economical and the technical features of the fuel cycle.

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Water–fuel ratio = 1.5 can be achieved with an extended fuel rod diameter or by the usage tight lattice with additional fuel rod's row (like VVER-S FA [7]). Obviously, the fuel loading increases in comparison with the standard FA.

Water–uranium ratio = 2.5 can be achieved by increasing inner hole in the fuel pellet or removal of some fuel rods from FA. In this case, the fuel loading can decrease in comparison with the standard FA.

It should be noted that any changes in the FA design can influence to the operational characteristics of the FA in the VVER core. In this paper, these changes are not considered.

This parametric investigation has goal to show the water–fuel ratio impact to the fuel cycle characteristics.

The neutron-physics calculations in this work were performed by the Consul code package [8]. All calculations were performed for the VVER-1000 reactor. Fuel campaign is 4 years with average burnup 49.3 MW d/kg HM.

2 The water–fuel ratio impact on the REMIX-fuel characteristics with HEU feeding

This section shows how the water–fuel ratio value affects to the REMIX-fuel characteristics with HEU feeding during multiple recycling. Such fuel is fabricated on the basis of the unseparated uranium and plutonium mixture from SNF reprocessing after irradiation in the VVER-1000 core and the HEU. The unseparated mixture fraction in the fuel is ~95%. All volume of the unseparated mixture from SNF is used to fabricate the REMIX-fuel. The fuel cycle flowchart with such fuel is presented in Figure 1.

In order to obtain the unseparated mixture (U + Pu) for REMIX-fuel fabrication for the first recycling step for all water–fuel ratio values (FA variants), a calculation of a standard UO_2 fuel cycle was performed, with an average enrichment of 4.1 wt.% and average burnup 49.3 MW d/kg_{HM}.

For the next recycling steps (from the second recycle), the unseparated mixture was taken from the SNF for each specific FA variant. For example, starting from second recycle during fuel fabrication for the FA with water–fuel ratio = 1.5, the reprocessed mixture ($UO_2 + PuO_2$) was taken from the SNF in the FA with the water–fuel ratio = 1.5. For others FA variants are similar.

Five sequential recycles were considered. On each cycle (recycle), the ^{235}U extra mass (as a part of HEU) fraction as a supplement to the unseparated mixture was selected to reach the same burnup 49.3 MW d/kg_{HM} as in open cycle with UO_2 (during the irradiation time). In Tables 1–3, these values for each FA are presented.

Average REMIX-fuel burnup was equal 49.3 MW d/kg_{HM}. Cooling, reprocessing and fuel fabrication duration take 5 years. During these processes, the disappearance of ^{241}Pu due to decay in the ^{241}Am, and transition of ^{239}Np in ^{239}Pu was taken into account. It should be noted, during the reprocessing process, all the minor actinides and FPs are removed from the SNF after each cycle. The fresh fuel does not contain americium.

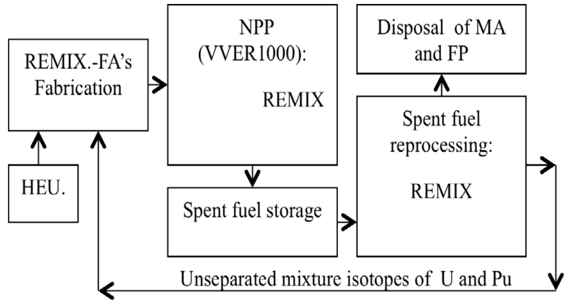

Fig. 1. Flowchart with REMIX-fuel with HEU feeding.

On the first recycle, the minimum ^{235}U consumption is observed when we use the FA with the water–fuel ratio = 2.5. The HEU enrichment in this case is about ~60%. The natural uranium consumption decreases 32% (if ^{235}U enrichment in the depleted uranium is 0.1%) compared to the open fuel cycle. Further, ^{235}U consumption increases. This is due to the fact that the ratio between the fissile isotopes (^{235}U, ^{239}Pu, ^{241}Pu) and absorbing isotopes (^{236}U, ^{240}Pu, ^{242}Pu) in the unseparated mixture which is required for REMIX-fuel fabrication before the second recycle less than before the first recycle.

On the first recycle, the maximum ^{235}U consumption achieved when we use the FA with water–fuel ratio = 1.5. In this case, the natural uranium economy is only 3% (if ^{235}U enrichment in the depleted uranium is 0.1%).

On the first recycle, natural uranium economy is 21.5% for the standard VVER-1000 FA.

After first recycle, there are no advantages in ^{235}U consumption for the slightly tight fuel lattice compared to the standard VVER-1000 fuel lattice. This is due to the fact that ^{240}Pu accumulates (after third recycle, shown in Tabs. 1–3) more significantly (almost 2-fold), than when using the standard VVER-1000 fuel lattice. On the five recycle, the natural uranium consumption reduces on 28% compared to the open fuel cycle (standard UO_2 fuel cycle with an average enrichment of 4.1 wt.%) (Fig. 2).

Tables 4–6 show information about the plutonium isotopic composition behavior during multiple recycling for each FA concepts.

Information about the plutonium fraction in the fresh REMIX-fuel on each considered cycle is presented in Figure 3.

How we can see from Tables 4–6, plutonium composition in the fuel changes little during multiple recycling for all FA concepts. These are differences in plutonium concentrations (predominantly ^{238}Pu, ^{240}Pu).

For the standard VVER-1000 FA, the plutonium content into the fresh fuel (or reactor core) after multiple recycling tends to 2% and stabilized (Fig. 3). There is a limit on the Pu content in the core. For the FA with water–fuel ratio equal 1.5, this value tends to 2.5%. This value is below the limit on 20%. If we use the FA with extended fuel lattice, the most minimum value (1.5–1.6%) of the Pu content is observed. This value is two times lower than the limit.

Table 1. REMIX fuel composition for FA with water/fuel ratio = 1.5.

Water/fuel ratio = 1.5	1 Recycle (%)	2 Recycle (%)	3 Recycle (%)	4 Recycle (%)	5 Recycle (%)
Unseparated mixture					
^{235}U	0.72	1.72	2.02	2.23	2.40
^{236}U	0.56	1.05	1.46	1.83	2.18
^{238}U	92.44	90.09	88.90	88.00	87.26
^{238}Pu	0.03	0.08	0.13	0.17	0.21
^{239}Pu	0.60	0.99	1.15	1.24	1.31
^{240}Pu	0.28	0.40	0.49	0.54	0.58
^{241}Pu	0.14	0.23	0.28	0.31	0.34
^{242}Pu	0.09	0.14	0.18	0.20	0.22
+HEU					
^{235}U extra mass fraction	4.13	3.24	3.10	3.06	3.03
^{238}U	1.03	2.07	2.29	2.40	2.47

Table 2. REMIX fuel composition for FA with water/fuel ratio = 2.0.

Water/fuel ratio = 2.0	1 Recycle (%)	2 Recycle (%)	3 Recycle (%)	4 Recycle (%)	5 Recycle (%)
Unseparated mixture					
^{235}U	0.72	1.02	1.21	1.32	1.39
^{236}U	0.56	0.97	1.35	1.69	2.01
^{238}U	92.44	91.26	90.44	89.84	89.35
^{238}Pu	0.03	0.06	0.10	0.12	0.14
^{239}Pu	0.60	0.71	0.76	0.80	0.82
^{240}Pu	0.28	0.36	0.39	0.40	0.41
^{241}Pu	0.14	0.19	0.21	0.22	0.23
^{242}Pu	0.09	0.17	0.22	0.24	0.25
+HEU					
^{235}U extra mass fraction	3.16	3.01	2.93	2.90	2.89
^{238}U	2.00	2.24	2.40	2.47	2.49

Table 3. REMIX fuel composition for FA with water/fuel ratio = 2.5.

Water/fuel ratio = 2.5	1 Recycle (%)	2 Recycle (%)	3 Recycle (%)	4 Recycle (%)	5 Recycle (%)
Unseparated mixture					
^{235}U	0.72	0.87	1.02	1.13	1.18
^{236}U	0.56	0.97	1.36	1.73	2.07
^{238}U	92.44	91.70	90.97	90.38	89.90
^{238}Pu	0.03	0.05	0.07	0.09	0.10
^{239}Pu	0.60	0.56	0.58	0.60	0.62
^{240}Pu	0.28	0.34	0.35	0.35	0.36
^{241}Pu	0.14	0.16	0.17	0.17	0.18
^{242}Pu	0.09	0.19	0.23	0.26	0.27
+HEU					
^{235}U extra mass fraction	3.08	3.17	3.16	3.10	3.07
^{238}U	2.08	2.00	2.08	2.18	2.24

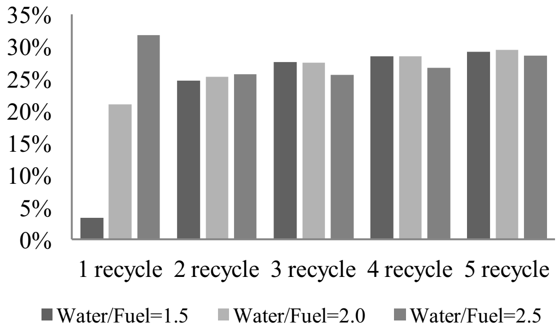

Fig. 2. Natural uranium consumption reduction for each FA concepts during multiple recycle.

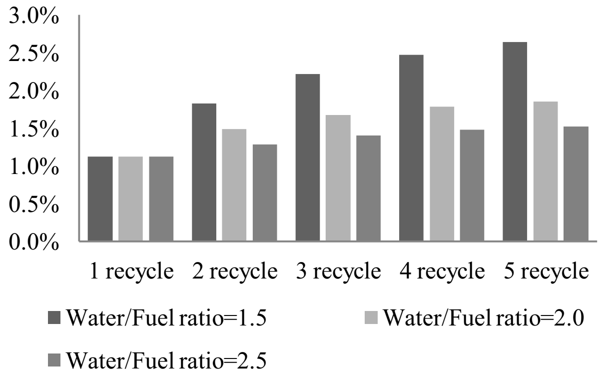

Fig. 3. The plutonium fraction in the fresh REMIX-fuel (for each FA concepts).

Table 4. Plutonium isotopic composition for FA with water/fuel ratio = 1.5.

Water/fuel ratio = 1.5	1 Recycle (%)	2 Recycle (%)	3 Recycle (%)	4 Recycle (%)	5 Recycle (%)
^{238}Pu	2.53	4.43	5.84	6.92	7.80
^{239}Pu	53.00	53.81	51.64	50.35	49.57
^{240}Pu	24.73	21.73	21.86	21.85	21.77
^{241}Pu	12.09	12.44	12.70	12.73	12.67
^{242}Pu	7.65	7.59	7.96	8.15	8.18

Table 5. Plutonium isotopic composition for FA with water/fuel ratio = 2.0.

Water/fuel ratio = 2.0	1 Recycle (%)	2 Recycle (%)	3 Recycle (%)	4 Recycle (%)	5 Recycle (%)
^{238}Pu	2.53	4.37	5.70	6.72	7.53
^{239}Pu	53.00	47.57	45.60	44.59	44.01
^{240}Pu	24.73	23.89	23.15	22.68	22.35
^{241}Pu	12.09	12.73	12.69	12.60	12.52
^{242}Pu	7.65	11.44	12.86	13.42	13.60

Table 6. Plutonium isotopic composition for FA with water/fuel ratio = 2.5.

Water/fuel ratio = 2.5	1 Recycle (%)	2 Recycle (%)	3 Recycle (%)	4 Recycle (%)	5 Recycle (%)
^{238}Pu	2.53	4.01	5.15	6.06	6.80
^{239}Pu	53.00	43.33	41.62	40.83	40.29
^{240}Pu	24.73	26.08	24.66	23.90	23.49
^{241}Pu	12.09	12.21	11.86	11.69	11.59
^{242}Pu	7.65	14.38	16.70	17.51	17.83

Therefore, 100% REMIX-fuel loading in the VVER-1000 core does not reduce the reactor safety performance during multiple recycling [5].

It should be recalled that, ^{238}Pu introduce a significant contribution in the residual heat. It is therefore important to monitor this value in the process of recycling. The most maximum value of the ^{238}Pu accumulation is observed for the FA with water–fuel ratio equal 1.5. In the future, it will require an estimate of the radiation characteristics and residual heat for fresh and burnt fuel.

Thus, we can conclude that, more ideal ^{235}U consumption achieved in the FA with a water fuel ratio equal 2.00 (standard VVER-1000 FA) for the base variant of the REMIX-fuel. There is no need to change anything in the core design.

3 The water–fuel ratio impact on the REMIX (MOX)-fuel characteristics with reactor grade Pu feeding

This section shows the water–fuel ratio value influence on the REMIX(MOX)-fuel characteristics with RgPu feeding during multiple recycling.

REMIX(MOX)-fuel is produced on a basis of the unseparated uranium–plutonium mixture from spent MOX-fuel on the first recycle (from the spent REMIX (MOX)-fuel – starting from two recycle) and RgPu from SNF UO_2 fuel for VVER-1000.

To obtain the spent MOX-fuel for the REMIX-fuel fabrication for the first recycling step for all FA concepts, the fuel loading with MOX-fuel was calculated. This calculation was made for the FA with water–fuel ratio equal 2.0 (standard for VVER-1000 FAs). An average RgPu mass fraction in the MOX-fuel is 9.5%. Average burnup is 49.3 MW d/kg_{HM}.

For the next recycling steps (after first recycle) the unseparated mixture (U + Pu) is taken from the spent REMIX(MOX)-fuel for each specific FA concepts.

Five recycles with this fuel were calculated.

On each recycle, RgPu mass fraction was chosen so that burnup was equal to the core with the standard VVER-1000 UO_2 fuel (49.3 MW d/kg_{HM}). For each FA concepts this condition is satisfied.

The fuel cycle flowchart is presented in Figure 4. In Figure 5 , information about RgPu consumption on the each recycle is presented.

The RgPu consumption decreases during multiple recycle for all considered FAs. This is due to the use of the SNF after each recycle.

On the first recycle, a maximal Pu consumption is observed, when we use the FA with the water–fuel ratio equal 1.5. This is due to the fact that we have a hard neutron spectrum in the region with the water–fuel ratio equal 1.5 due to the reduction of the water nuclei number. However, this allow to increase the plutonium content in the spent REMIX(MOX) fuel after first recycle (according to Fig. 6). The breeding ratio for the water–fuel ratio 1.5 is higher than for to the water fuel ratios 2.0 and 2.5. Further, plutonium consumption decreases compared to the water–fuel ratios 2.0 and 2.5.

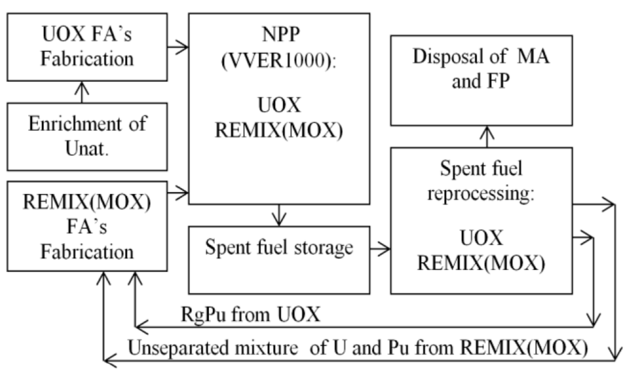

Fig. 4. The flowchart with REMIX(MOX)-fuel.

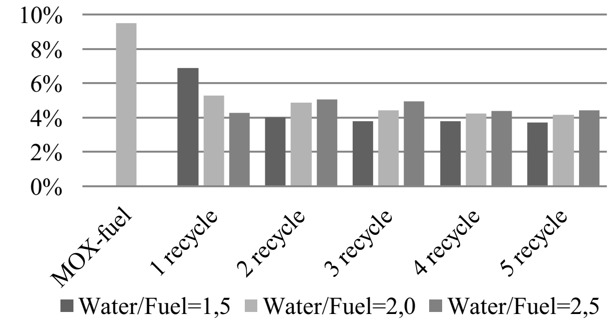

Fig. 5. RgPu consumption on the each recycle during the multiple recycling of the REMIX(MOX)-fuel for each FA concepts.

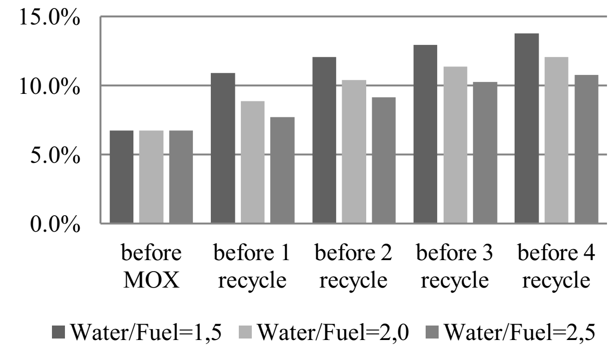

Fig. 6. The plutonium fraction in the unseparated mixture of the U and Pu isotopes, which is required for REMIX(MOX)-fuel fabrication (for each FA concepts).

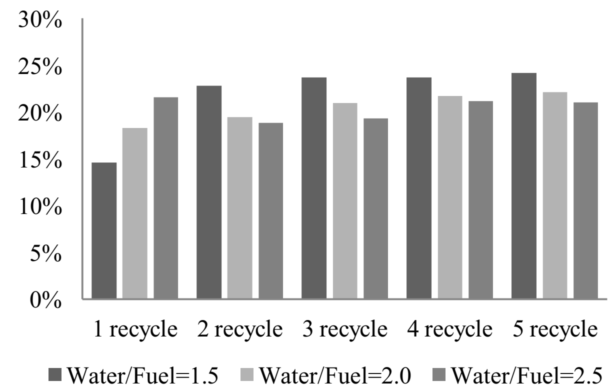

Fig. 7. Natural uranium consumption reduction for each FA concepts during multiple recycle.

On the five recycle, we show the minimum RgPu consumption for the FA with the water–fuel ratio equal 1.5. In this case, according to Figure 7, the natural uranium consumption reduces on 24% compared to the open fuel cycle (standard UO_2 fuel cycle with an average enrichment of 4.1 wt.%).

It should be noted that, this fuel is not loaded in the 100% VVER-1000 core, because the FA have high Pu content (according to Fig. 8). There is a limit on the Pu content in the core.

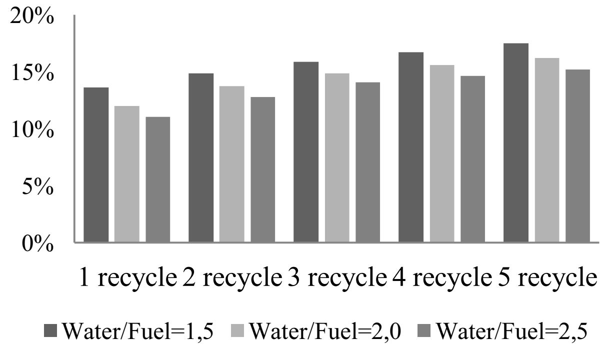

Fig. 8. The plutonium fraction in the fresh REMIX(MOX)-fuel (for each FA concepts).

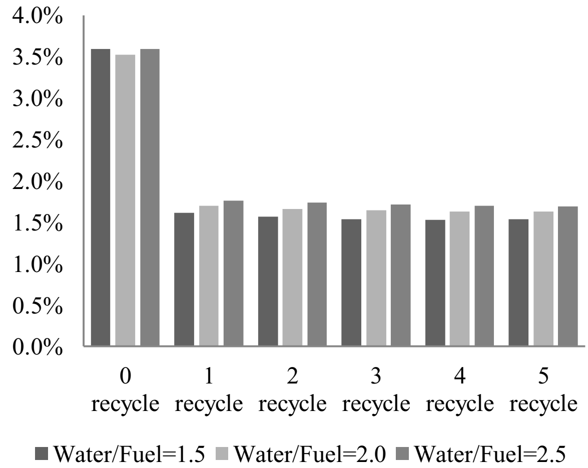

Fig. 10. ^{233}U feeding on each recycle (for each FA concepts).

4 The water–fuel ratio impact on the REMIX (Th)-fuel characteristics with ^{233}U feeding

This section shows how the change in the water–fuel ratio in the VVER FA affect on the REMIX(Th) fuel characteristics, which is formed on the basis of the unseparated uranium–thorium mixture and ^{233}U. This is a fundamentally new REMIX-fuel. The natural uranium is not used for the fuel fabrication. Thorium can be obtained by reprocessing of the monazite sand. Also, thorium is the source of the secondary fissile material ^{233}U.

Flowchart with REMIX(MOX)-fuel is presented in Figure 9. Such fuel consists of the thorium–uranium unseparated mixture, a small amount of the natural thorium and ^{233}U from blankets of the fast breeder reactors. To get the thorium–uranium unseparated mixture for the REMIX(Th)-fuel fabrication for first recycle the fuel loading with composition: $^{233}UO_2$–ThO_2 was calculated (0 recycle). These calculations were carried out for each FA concept.

Five recycles with this fuel were calculated. At each cycle, ^{233}U feeding was chosen so that burnup was equal to the core with the fuel: $^{233}UO_2$–ThO_2 that is 50.0 MW d/kg$_{HM}$. The information about ^{233}U feeding, which is required for the implementation of the 4 years fuel campaign is presented in Figure 10. On the first recycle, for each FA concepts is taken uranium–thorium mixture from the corresponding FA. For example, for the REMIX-fuel production for first recycle for the FA with a slightly tight fuel lattice (water–fuel ratio = 1.5) you need to take the uranium–thorium mixture from the spent FAs with slightly tight fuel lattice.

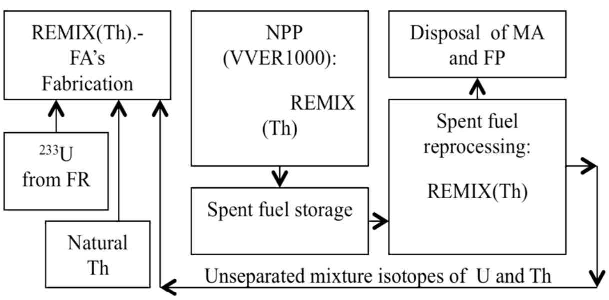

Fig. 9. The flowchart with REMIX(MOX)-fuel.

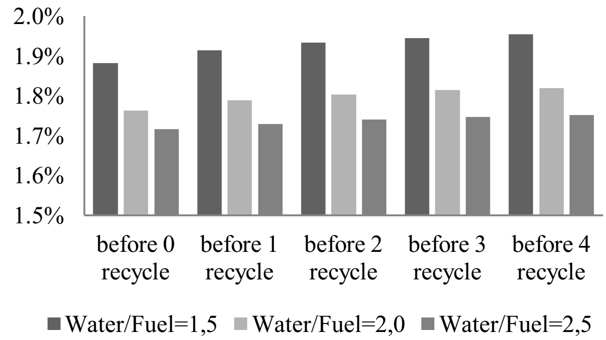

Fig. 11. The ^{233}U fraction in the unseparated mixture of the U and Pu isotopes, which is required for REMIX(Th)-fuel fabrication (for each FA concepts).

For the REMIX-fuel production for each recycles, we take all of the unseparated mixture from the SNF. During reprocessing, the accumulated FPs and minor actinides are separated. The duration of SNF aging in the intermediate storage, reprocessing of SNF and fabrication processes is 5 years. It should be noted that in this case there is no accumulation of minor actinides and FPs. Duration of the fuel campaign is 4 years.

As we can see in Figure 11, at the first recycle optimal consumption of the fissile material, ^{233}U is observed for the standard FAs.

There is minimum ^{233}U consumption when we use FA with slightly tight fuel lattice rods, because in this case the biggest value of the breeding ratio of the fissile isotope is observed. This is appropriate for all recycles. Compared with the initial cycle of the uranium–thorium fuel consumption of ^{233}U was reduced to 2 (for the FA with water–fuel ratio equal to 2.5) – 2.3 (in the FA with water–fuel ratio equal to 1.5) times (Fig. 12).

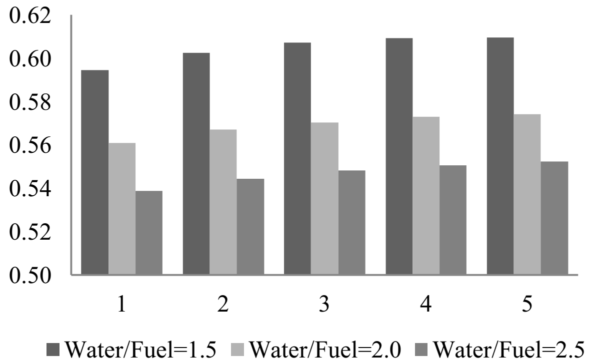

Fig. 12. Breeding ratio.

5 Conclusions

For the traditional REMIX-fuel does not make sense to change anything in the design of VVER FA, because there are no advantages in the fuel feed consumption. The natural uranium economy by the fifth cycle reached ~29%.

REMIX fuel based on uranium–plutonium from SNF MOX fuel, it would be appropriate to use the FAs with water–fuel ratio 1.5 (This is because, the flow rate of reactor-grade plutonium on the four recycle is at 15% lower than in the standard FA.). Economy of the natural uranium is 24%.

However, FA with water–fuel ratio 1.5 increases the flow resistance and complicate cooling FAs in emergency operation.

For the REMIX-fuel based on the thorium, the optimal design of the FA for multiple fuel cycle is the design of the FA with slightly tight fuel lattice (water–uranium ratio of ~1.5). In this case, the natural uranium not used for the fuel fabrication.

Any changes in the FA design can cause the operational characteristics of the FA in the core.

The reported study was funded by RFBR according to the research project No. 16-38-00021.

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Cite this article as: Evgenii Bobrov, Pavel Alekseev, Alexander Chibinyaev, Pavel Teplov, Anatoliy Dudnikov, The choice of the fuel assembly for VVER-1000 in a closed fuel cycle based on REMIX-technology, EPJ Nuclear Sci. Technol. 2, 42 (2016)