критерия поддержания содержания ^{232}U и ^{236}U на всех переделах производства топлива из ОЯТ РБМК в допустимых пределах и выполнение работ по снижению погрешности расчета изотопного состава ОЯТ позволит существенно увеличить долю пригодных для переработки ОТВС.

Возможность применения выделенного из ОЯТ РБМК плутония при производстве МОХ-топлива, производстве источников энергии на основе ^{238}Pu может значительно увеличить потребность в переработке ОЯТ РБМК по сравнению с его использованием только в качестве несырьевого источника ^{235}U.

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Prospects and practicality of RBMK SNF reprocessing

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Introduction

The nuclear power plants (NPP) housing RBMK-1000 reactors have accumulated large stocks of spent nuclear fuel (SNF). The main way of the spent fuel management there is dry storage of fuel rod bundles in TUK-109 casks subsequently transferred to the centralized storage facility at the Mining and Chemical Combine. This technology is developed for the conforming spent fuel assemblies (acceptable for long-term storage). The ways of management of non-conforming SFAs are under development now. One of them could be their reprocessing at the RT-1 Plant at Mayak PA. This would not only discharge the spent fuel from reactor cooling pools and NPP spent fuel storage facilities, but also engage the RT-1 plant capacities, which will soon be available after the programs on utilization of decommissioned nuclear submarine and surface ship cores is completed.

In 2010, Rosatom State Corporation initiated efforts to ensure safe handling of the RBMK spent fuel and to study their reprocessing practicability. The project is designed to remove eight non-conforming SFAs from the Leningrad NPP to Mayak PA and to prepare regular shipments of the non-conforming RBMK SNF for reprocessing. In most cases the non-conforming SNF is the fuel assemblies unloaded from the core ahead of schedule that did not reach their design burn-up and have a big share of uranium-235. Taking a decision on large-scale reprocessing of the RBMK SNF requires estimating the quantity of reprocessable SFAs.

Reprocessing can become relevant for the conforming SNF, as well. For example, the Leningrad NPP annually adds about 1500 SFAs to the spent fuel accumulated at its four power units. Since the capacity of Division for SFA Disassembling and SNF loading into TUK-109 cask is 3600 SFA/year, the total decrease in the amount of the spent fuel does not exceed ~ 2000 SFA/year. Thus, reprocessing a big amount of the conforming SNF would facilitate the RBMK SNF management issues.

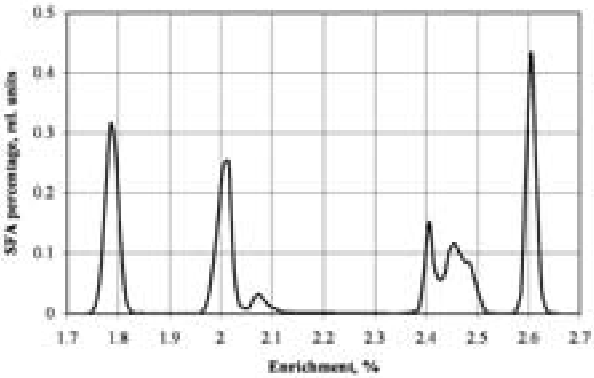
1. Array of the RBMK SNF under storage

The SNF reprocessing feasibility depends on three main parameters: the fuel initial enrichment in U-235, burn-up and the SNF cooling period.

Let us consider a specific example of the Leningrad NPP SNF having in mind that the situation with the RBMK reactors at other NPPs is similar. As of the end of 2010, there were more than 40,000 SFAs with the initial enrichment ranging from 1.8 to 2.8% stored. The percentage of the spent fuel assemblies with regard to their enrichments is as follows: 1.8 – 12.0%; 2.0 – 36.4%, 2.4 – 27.5%, 2.6 – 17.8%, 2.8 – 6.3%.

Fig.1 presents the SFA percentage with regard to the real enrichment. It demonstrates that the dispersion of the initial enrichment is more than fuel was made of both natural and regenerated uranium.The SFA quantity in terms of the fuel burn-up for the enrichments ranging from 1.8 to 2.6% is given in Fig.2.

The pictures demonstrate that the fuel enrichments and burn-ups vary widely that makes us assume a big number of reprocessable SFAs.



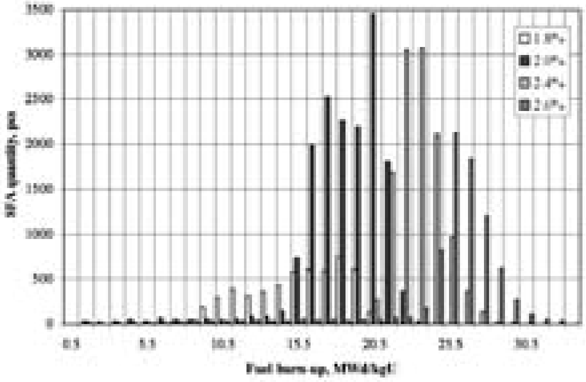


Fig.1. SFA percentage in terms of real initial enrichment

Fig.2. SFA quantity in terms of burn-up for different fuel enrichments

2. Practicality of the RBMK SNF reprocessing

The RBMK-1000 SNF reprocessing is aimed at involving the ^{235}U in the fuel cycle. The uranium regenerated from the RBMK SNF can be involved in the nuclear fuel cycle either by down-blending uranium products of the reprocessed SNF from different reactor facilities to achieve the required parameters of the final products in terms of useful isotopes, or by the re-enrichment in the complete reprocessing cycle (radiochemical, sublimate and separating production). A criterion to assess the SNF reprocessing practicability is proposed in [1]. This is the quality of uranium regenerated from the spent fuel (hereinafter, the quality factor), which is determined from the following expression:

$$G_{\text{п}} = \frac{[^{235}U_{\text{р}}]-[^{235}U_{\text{о}}]}{[^{235}U_{\text{п}}]-[^{235}U_{\text{о}}]},$$

where the numerator is the difference of ^{235}U concentration in the feed and waste streams, and the denominator is the difference of ^{235}U concentration in the product and waste streams.

If the feed material is the regenerated uranium, then $[^{235}U_{\text{р}}]$ is ^{235}U concentration in the SNF. In its turn, the ^{235}U concentration in the product stream is calculated from the formula:

$$[^{235}U_{\text{п}}]=[^{235}U_{\text{э}}]+K_1 \cdot K_2 \cdot [^{236}U_{\text{р}}],$$

where $[^{235}U_{\text{э}}]$ is the uranium effective concentration in the product stream (the required enrichment);

$[^{236}U_{\text{р}}]$ is ^{236}U concentration in SNF;

K_1 is the ^{236}U compensation factor in the regenerated uranium;

K_2 is the multiplier that takes into account a partial ^{236}U discharge in the waste (equals 0.8).

In production of the VVER fuel with an enrichment of 4.9% from natural uranium that does not contain ^{236}U, the average quality factor is 0.127 with a ^{235}U concentration of 0.1% in the waste. Actually, natural uranium with a quality factor of 0.08-0.1 and more is used.

Thus, assessing practicability of the RBMK spent fuel for production of the VVER fuel, it is necessary to determine the maximum burn-up for each initial enrichment; the quality factor for the maximum burn-up shall not be less than 0.127.

2.1. Calculations of the quality factor for uranium regenerated from RBMK SNF

Table 1 and Fig.3 present the quality factors for the uranium regenerated from RBMK SNF to produce the VVER 4.9%-enriched fuel. Consideration was given to the uranium separated from the spent fuel assemblies with different burn-ups and enrichments made of natural and regenerated uranium. The ^{235}U concentration in the waste was taken equal to 0.1% and the ^{236}U compensation factor in the regenerated uranium (K_1) made up 0.3. The RADIONUCLIDE code [2] was used to calculate the nuclide composition of the spent fuel assemblies. The quality factor for the regenerated uranium with one and the same fuel enrichment is higher when the regenerated uranium is used as a feed material; this happens due to the excessive quantity of ^{235}U used to compensate ^{236}U in production of the RBMK fuel.

Table 1. The quality factor for the uranium regenerated from the RBMK fuel with different initial enrichments and burn-ups

Enrichment, %		1.8	1.8	2.0	2.0	2.4	2.6
Feed material		Natural uranium	Regenerated uranium	Natural uranium	Regenerated uranium	Regenerated uranium	Regenerated uranium
Fuel burn-up, MWd/kgU	5.0	0.2458	0.2564	0.2849	0.2948	0.3730	0.4128
	10.0	0.1625	0.1726	0.1968	0.2068	0.2781	0.3156
	15.0	0.0982	0.1071	0.1260	0.1356	0.1977	0.2319
	20.0	0.0511	0.0581	0.0724	0.0800	0.1309	0.1607
	25.0	0.0196	0.0245	0.0339	0.0397	0.0781	0.1023
	30.0	-	-	-	-	0.0392	0.0572
	35.0	-	-	-	-		0.0253

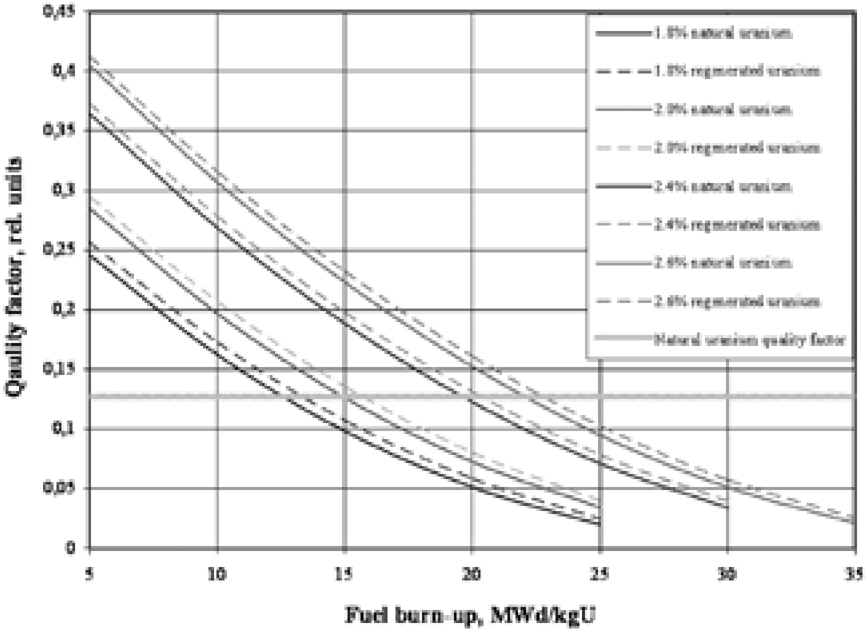


Fig.3. Burn-up dependence of the quality factor for the uranium regenerated from the RBMK SNF

2.2. Estimates of the SFAs acceptable for fabrication of the VVER fuel by the re-enrichment in the complete reprocessing cycle

Table 2 presents the RBMK fuel burn-up, which makes it adequate to involve the regenerated uranium in the complete reprocessing cycle with re-enrichment (radiochemical, sublimate and separating production).

Table 2. Maximum fuel burn-up of the reprocessable RBMK SFAs in case of re-enrichment of the regenrated uranium in the complete reprocessing cycle

Enrichment, %	1.8		2.0		2.4		2.6	
Feed material	Natural uranium	Regenerated uranium	Natural uranium	Regenerated uranium	Natural uranium	Regenerated uranium	Natural uranium	Regenerated uranium
Maximum fuel burn-up, MWd/kgU	12.6	13.3	15.0	15.7	19.6	20.3	22.0	22.7

To determine the quantity of the reprocessable SFAs in case of re-enrichment of the regenrated uranium in the complete reprocessing cycle, it is necessary to estimate the quantity of those with a burn-up that does not exceed the values given in Table 2 on the basis of the SFA burn-up percentage (Fig.2). However, Fig.2 presents aggregate data for each initial enrichment with no account taken for the feed material. As seen from Table 2, the maximum fuel burn-up (from the viewpoint of reprocessability) depends on the feed material used for fabrication; for the regenerated uranium it is higher by ~0.7 MWd/kgU. To find out which burn-up value (Table 2) should be used, we should refer to Fig.1. The SFA percentage in terms of the initial enrichment demonstrates that:

- The fuel assemblies with the initial enrichment of 1.8 and 2.6% were made of natural uranium,
- Natural uranium was used for fabrication of most of the 2%-enriched fuel assemblies (more than 90%),
- For the 2.4%-enriched fuel assemblies, the natural and regenerated uranium was used in similar portions.

Thus, the following burn-up values were used to determine the quantity of the reprocessable SFAs stored at the Leningrad NPP:

For SFAs with the enrichments of
1.8 % – 12.6 MWd/kgU,
2.0 % – 15.1 MWd/kgU,
2.4 % – 20.0 MWd/kgU,
2.6 % – 22.0 MWd/kgU,

The obtained results are presented in Table 3. The total quantity of the SFAs that can be utilized for fabrication of the VVER reactor fuel with an enrichment of 4.9% is ~ 5000 that makes up not less than 12% of the total quantity of the spent fuel stored at the Leningrad NPP.

The presented data do not take into consideration the error of the SFA burn-up averaging (±4 %) and the error of the ^{235}U content determination that makes up ±3 % in accordance with the RADIONUCLIDE data.

Their effect is essential (Table 3), especially when the maximum burn-up of the reprocessable SFAs is close to the peak of the SFA distribution in terms of burn-up. That was observed for the SFA with the enrichments of 2.0 and 2.4%.

However, even if the averaged burn-up or ^{235}U content in the SNF is systematically decreased, the quantity of the reprocessable SFAs remains significant.

Table 3. Quantity of the reprocessable RBMK SFAs stored at the Leningrad NPP

Enrichment, %		1.8	2.0	2.4	2.6
Quantity of SFAs acceptable for reprocessing	With no account taken for the error of determination of burn-up and ^{235}U content in SNF	1483	1690	833	663
	With account taken for the error of burn-up determination within the range of [-4.4]%	1292 – 1662	1046 – 2784	576 – 2091	603 – 803
	With account taken for the error of ^{235}U content determination within the range of [-3.3]%	1350 – 1604	1247 – 2282	661 – 1343	640 – 699

The above-mentioned estimates refer to the SFA as a whole. If we consider a possibility to reprocess separate fuel rod bundles, we will see a different situation, since the burn-up of the upper and lower fuel rod bundles in the RBMK SFAs differs significantly.

The average burn-up in the lower bundle is much higher (more than by 10%) than that in the upper bundle; so, the estimates of the SFAs acceptable for preprocessing that do not take into account the burn-up distribution is underrated. In some SFAs, both bundles are reprocessable; moreover, there is a big number of the SFAs with reprocessable upper bundles.

2.3. Use of the RBMK SNF for fabrication of the MOX fuel and other purposes

The RBMK SNF reprocessing will provide not only an additional source of uranium, but also allow utilizing other SNF components.

The plutonium produced from the RBMK SNF can be used together with weapon-grade plutonium for fabrication of the MOX fuel for the BN reactors. As is known, the agreement on utilization of 34 tons of weapon-grade plutonium provides for down-blending of up to 12 wt.% of power-grade plutonium to get the required isotopic composition. The plutonium produced from the RBMK SNF could add to the accumulated stocks of plutonium of different origin and that separated from the VVER-440 SNF used for that purpose. This would make adjusting the plutonium isotopic composition more precise, since in the RBMK SNF it varies in a wider range than in the VVER-440 SNF.

Table 4 presents Pu content (in absolute units and percentage) in the 2.4%-enriched SFAs as of the core defueling date for different burn-ups. The calculations demonstrate that the demand for power-grade plutonium for MOX fuel production can be completely satisfied provided that plutonium produced from the RBMK SNF (even that stored for a long time) is used.

In addition to uranium and plutonium isotopes, the RBMK SNF contains a big quantity of other useful nuclides. Table 4 presents the content of ^{237}Np and ^{241}Am to estimate the quantity of the feed material for production of ^{238}Pu isotope. It is seen that the content is significant, so the RBMK SNF can be considered as a valuable source of feed materials for production of ^{238}Pu-based energy sources. The heat released as a result of ^{238}Pu decay (0.56 W/g) allows using it as a source of energy in thermal and electric generators for pacemakers, space satellites, infrared beacons, etc. Such plutonium sources in Voyager spacecraft enabled sending images of planets to the Earth for a long period of time. After beta-decay, ^{241}Pu isotope (half-life is 13 years) turns into ^{241}Am that is used as a filler in most smoke detectors.

Table 4. The content of useful nuclides in the RBMK SNF versus 2.4%-enriched SFA burn-up. The feed material is natural uranium

Nuclide	**Fuel burn-up, MWd/kgU**							
	5		10		15		20	
	g/tU	%	g/tU	%	g/tU	%	g/tU	%
Pu-238	0.6	0.03	3.7	0.13	10.9	0.28	24.6	0.52
Pu-239	1490.0	85.33	2195.6	72.65	2490.7	62.01	2571.9	53.23
Pu-240	219.8	12.59	647.8	21.43	1130.0	28.13	1601.3	33.14
Pu-241	33.9	1.94	154.4	5.11	310.4	7.73	459.2	9.50
Pu-242	1.9	0.11	20.6	0.68	74.4	1.85	174.6	3.61
Total Pu isotopes	1746.2		3022.1		4016.4		4831.6	
Np-237	13.5		37.9		69.6		106.7	
Am-241	0.28		2.76		8.6		17.0	

3. Selection of SFAs to be reprocessed

Considering the re-enrichment in the complete reprocessing cycle, paper [1] suggests that the SFAs should be categorized as “rich” and “poor” using the regenerated uranium quality factor as a criterion. The “rich” category SNF is suggested to go through the closed reprocessing cycle (radiochemical, sublimate and separating production), while the “poor” one – through the shortened cycle confined to production of triuranium octoxide. To avoid reprocessing of the “poor” category SNF that would decrease productivity of the radiochemical processing line and accumulate waste, it is necessary to sort out the RBMK SFAs by the SNF categories.

The scope of work will depend on the established goals that can be different:

1. to make maximum use of the RBMK SNF as a source of non-raw uranium including the re-enrichment by down-blending uranium products regenerated from the spent fuel of different nuclear facilities,
2. to reprocess the SNF only to decrease the severity of the SNF storage problem at NPPs housing the RBMK reactors,
3. to resolve both issues.

Solutions to the first or third problems will require some efforts to decrease the error of determination of the ^{235}U and Pu isotope content with account taken for the following factors:

- actual conditions for in-reactor SFA irradiation (history of the SFA charging) and nuclear plant loads;
- process errors (and their variations with time) during fabrication of the fuel and the fuel assemblies;
- errors of averaging the burn-up over SFA, etc.

The key issue is adjusting the predictive model of the fuel nuclide composition based on MCU benchmark calculations and verifying the adjusted model using experimental data on the fuel nuclide composition that will allow refining the error of actinide content calculations.

Solutions of the above tasks will make it possible to sort out the “poor’ category SNF.

Using the selected ways of the initial data presentation and the predictive model of the SNF nuclide composition, it is necessary to calculate the regenerated uranium quality factor and develop a reprocessable SFA database.

Conclusions

The estimated quantity of reprocessable RBMK SFAs that can be used for production of 4.9%-enriched fuel for the VVER reactors make us state that the involvement of such SNF in the fuel cycle as a non-raw source of ^{235}U is practical in the nearest future.

Refinement of the criterion for taking a decision on appropriateness of the SNF reprocessing (both in terms of determination of the coefficient errors, and methodology), addition of criterion for maintaining ^{232}U and ^{236}U content within admissible limits at all stages of the fuel production from the RBMK SNF and decrease of the SNF isotopics calculation error will allow increasing the quantity of reprocessable SFAs significantly.

Thus, reprocessing the RBMK SNF will provide an opportunity to use not only ^{235}U as a non-raw source for production of the VVER fuel, but also ^{239}Pu for production of the MOX fuel for the BN reactors and ^{238}Pu-based sources of energy.

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