EVALUATION OF TECHNICAL AND ECONOMIC INDICATORS OF REMIX FUEL APPLICATION IN THE LWR FUEL CYCLE

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Abstract

Various ways of using reprocessed uranium and plutonium in closed nuclear fuel cycle (NFC) of thermal-neutron reactors by reprocessing spent nuclear fuel (SNF) from nuclear power plants with release of these materials and manufacturing of secondary fuel are described.

1. INTRODUCTION

One of the main problems with SNFs reprocessed uranium reuse is the accumulation of ^{232}U that generates a chain of short-lived high-power gamma emitters [1]. Another reason for limiting use of reprocessed uranium (rep U) is the accumulation of ^{236}U which is a neutron absorber. Its presence requires additional enrichment which reduces efficiency of fuel cycle option [2]. Separated plutonium also has to be thoroughly cleaned before refabricating to MOX or REMIX fuel.

U and Pu nuclide composition degradation in SNF, caused by increased burnout, leads to changes in the technological schemes for the reprocessing of SNF. Modern extraction technology for reprocessing SNF originated more than 50 years ago in the USA for reprocessing irradiated natural uranium for military purposes [3]. It was called PUREX process (PUREX = Plutonium-Uranium Extraction). In Russia, the EDC (Experimental Demonstration Center) technology at the MCC plant incorporates the improvement of technological processes for effluent discharges elimination (no technological low-level waste (LLW) based on PUREX process) [4].

Reprocessing of spent fuel is considered in order to use the energy potential of the remaining uranium and accumulated plutonium to eliminate the long term storage of SNF and products of reprocessing and to save 20–30% of natural uranium [5].

Today, about 24 thousand tons of spent nuclear fuel has been accumulated in Russian Federation. Each year, about 650-–700 tons of spent fuel is unloaded from the reactors of Russian nuclear power plants (NPP), while no more than 15% of this volume is reprocessed [6]. Regenerated nuclear materials (RepU and Pu) have been traditionally used in Russia separately. Reprocessed uranium has been enriched and used mainly in RBMK reactors. Plutonium has been stored to start the fast reactor program, but now the fabrication of MOX fuel for BN-800 is started. The concept of two-component nuclear energy system has appeared in Russian Federation, including both reactor types (VVER and BN) [7]. The transition period may include reuse of reprocessed nuclear materials as mixed fuel for LWRs (like VVERs) in terms of more effective using than MOX fuel with partial core loading.

2. MODELING OF NUCLEAR FUEL CYCLES

Since 2005 JSC "Khlopin Radium Institute" (KRI) in cooperation with NRC «Kurchatov institute» has been developing the REMIX fuel (Regenerated Mixture of U-Pu oxides), supposing the joint reuse of regenerated U and Pu for loading the whole zone of the existing VVER-1000/1200 [5, 2].

The authors of the work carried out numerous calculations by SCALE code system [6]. SCALE code system is a set of tools that allow to carry out calculations of criticality, fuel burnout, materials activation,

characteristics of radiation sources and radiation protection. In this work two computational sequences under control of TRITON and MAVRIC modules were used. Three-dimensional model of infinite reactor core with FA TVS-2M [9] was used for simulation. The neutron multiplication factor during fuel depletion was kept at k_{eff} =1 by controlling the concentration of boron in the coolant.

Various models of nuclear fuel cycles (NFC) were simulated using mixed uranium-plutonium fuel. The analysis considered a group of thermal reactors of Russian design VVER-1000/1200. LWRs' SNF is to be processed during their further period of operation. After burning up and cooling the fuel, isotopic composition of SNF is evaluated for the possibility and reasonability of its reuse. With the residual energy potential of the burned fuel is higher than that of natural uranium, nuclear materials from this fuel is used in the next recycling simulation. The article deals with the main options of nuclear fuel cycles based on mixed U-Pu fuel.

3. THE TECHNOLOGICAL ASPECTS OF REGENERATED URANIUM MULTIPLE RECYCLING

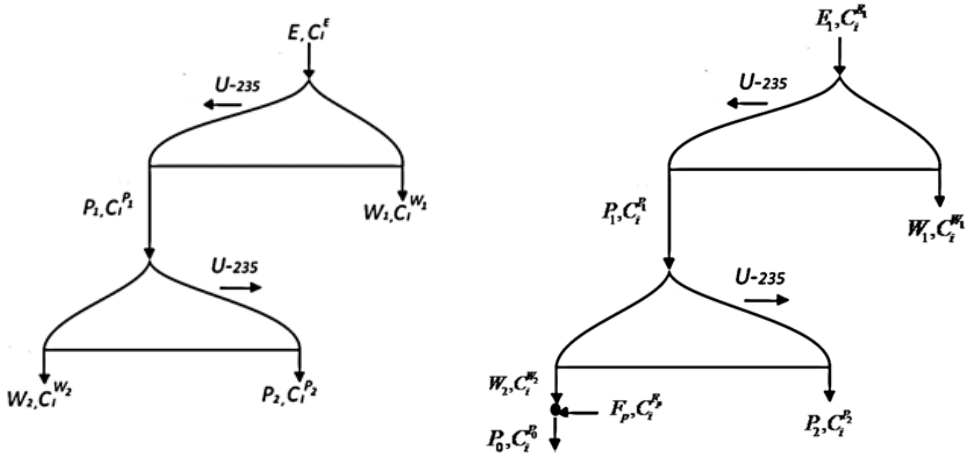
The re-enrichment of reprocessed uranium is one of the key technologies in development of REMIX-fuel.

^{232}U is a threat to radiation safety due to presence of the ^{208}Tl in the decay chain. This isotope emits high energy photons (~2.61 MeV) which leads to necessity of organizing the protection for people and equipment. ^{232}U content in Russia is limited at the level ~$2.0\cdot10^{-7}$ U wt.% for VVER fuel. At present time regulating restriction to RBMK fuel is softer ~$5.0\cdot10^{-7}$ ^{232}U wt.%.

^{236}U is an additional neutron absorber. This fact determines the necessity to compensate its presence by additional enrichment in ^{235}U.

^{234}U content is limited by 20 000 μg/g ^{235}U according to ASTM C996-96 specification due to its alpha activity. This specification is not extremely hard: typical restriction to this value is 10 000 or 11 000 μg/g ^{235}U (IAEA TECDOC-1529). After burning up to ~47 GW·day/tHMi the ratio of ^{234}U and ^{235}U can reach the value of ~17 945 μg/g in reprocessed uranium before the enrichment and will obligatory exceed 20 000 μg/g at the very first stages of cascade enrichment in case of direct enrichment approach in the ordinary cascade without natural uranium feed.

Development of reprocessed uranium re-enrichment approach must meet the demand to eliminate the excess of reprocessed uranium, which is not involved on the stage of fuel fabrication. Excepting RepU from the first recycle, this demand can hardly meet with implementation of ordinary cascade due to strong restriction on ^{232}U content. To avoid the problem dealt with restriction on ^{232}U content, the double cascade enrichment approach can be used. The main idea of this approach is to implement spatial separation of two fractions: first part of uranium flow with high ^{232}U content, second and the main part with relatively low concentration of this isotope. The example of cascade scheme which allows to implement this approach is shown at FIG.1 (a). The problem is that the the amount of secondary fuel in several times less than the original SNF from natural uranium. To provide necessary volume of fuel which is sufficient to the purpose of annular fuel loading fabrication the special enrichment technique is needed. The example of the cascade scheme, which is appropriate for this purpose, is shown at Fig. 1 (b) [15].



a b

FIG. 1. Double cascade schemes for multi recycled uranium re-enrichment

Where F_i, P_i, W_i – flows of Feed, Product and Waste of cascade, E_i – RepU flow, C_i – concentrations of isotopes in the flows. For fuel fabrication purpose in case a) W_2 flow is used. In case b) the P_0 is a flow of uranium which is appropriate for the fuel fabrication purpose. It is made from mixture of W_2 and F_p flows, where F_p is low enriched uranium made from natural uranium. P_2 flow is uranium with 20% enrichment and extremely high concentration of ^{232}U. Mass of this fraction is less than 3% of the initial mass of recycled uranium. Excepting P_2 fraction, practically full amount of recycled uranium is used for the purpose of secondary fuel fabrication.

4. REMIX-A

REMIX-A is a basic option. During the reprocessing of spent fuel, the recovered U and Pu are separated (not necessarily completely) and re-mixed in the original ratio with enriched uranium (19% ^{235}U) to provide necessary energy potential for future fuel. The requirement to enrich natural uranium up to 19% of ^{235}U is based on the non-proliferation issues. Multi-recycling of such fuel is possible but about 15% of excess RepU is generated on each recycling. If we could use the feed of highly enriched uranium (about 55–65% of ^{235}U), recycling occurs without the formation of excess reprocessed uranium.

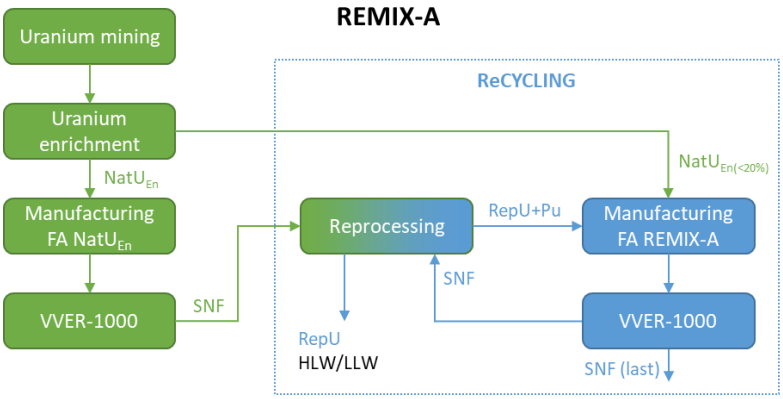


FIG. 2. REMIX-A recycling schematic model at enrichment of feed up to 19% for 235U

The REMIX-A recycling schematic model is shown in Figure 2. Seven cycles are considered. First cycle (highlighted in green) is the starting load of enriched natural uranium fuel. In this option, as a result of reprocessing and reuse of regenerated materials, it is possible to reduce the final accumulated amount of SNF about 4 times compared to an open fuel cycle. Natural uranium saving of 25–30% is achieved.

5. REMIX-C

REMIX-C assumes the re-enrichment of reprocessed uranium up to 4–5% ^{235}U. Then it is mixed with plutonium-uranium master mixture left in reprocessing plant and with enriched natural uranium (4–5% ^{235}U). Excess of nuclear materials is eliminated, but there is a necessity to transport reprocessed uranium to the plant for re-enrichment and back.

From the point of view of fuel supply for Russian-designed reactors built in other countries for all period of operation, REMIX-C option can be considered as an optimal. Russian Federation assumes to provide services for reprocessing of SNF and returning nuclear materials (mixed U-Pu fuel) and radioactive waste to the customer. The number of such fuel cycles (~7) is enough for all operating time of the reactor facility. With this approach the customer gets rid of the problem of long-term storage of SNF, because it does not accumulate during operation.

The REMIX-C recycling schematic model is shown in Figure 3. After seven cycles the amount of SNF is reduced by seven times. Natural uranium saving is about 30%.

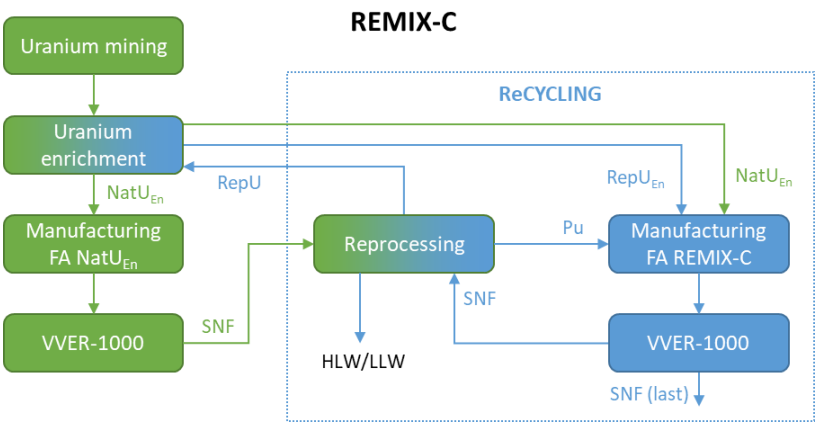


FIG. 3. REMIX-C recycling schematic model

6. REMIX-B

REMIX-B option assumes no natural enriched uranium feed using as well as the total volume of nuclear materials reduction. Plutonium content in the fuel can reach more than 4%. After burning up to ~47 GW·day/tHMi about 1.25% of plutonium accumulates in SNF. For one FAs with REMIX B with a plutonium content of 4%, you can use regenerated products from reprocessing 3–4 spent FAs. Feeding with enriched natural uranium is not provided, in the same time you need to provide the RepU direct enrichment. The fabrication of REMIX-B fuel requires a high accuracy of mixing of components with non-constant energy potential. However, the amount of secondary fuel is several times less than the original SNF from natural uranium.

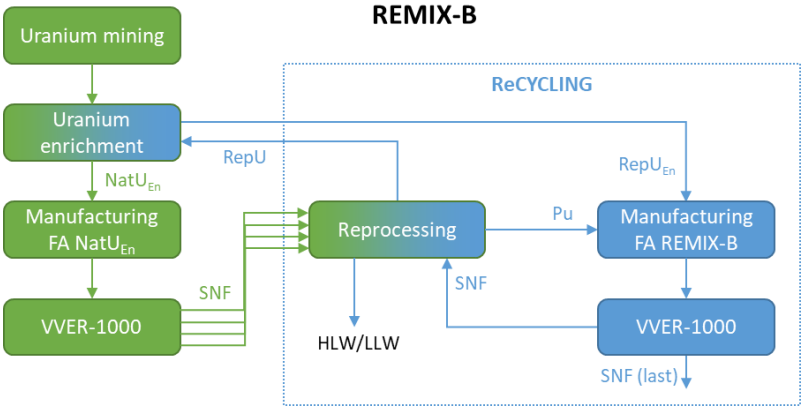


FIG. 4. REMIX-B recycling schematic model

REMIX-B recycling schematic model is shown in Figure 4. Due to the lack of NatU feeding fuel is “compressed” and plutonium concentration increases at each cycle. This option is limited in the number of cycles due to the high plutonium content. At the first recycling plutonium content starts from 4%, at the second from 8%. Reduction of SNF by 4 times compared to open nuclear fuel cycle is achieved after one. The reduction of SNF amount after two cycles is 10 times. Natural uranium saving is about 25–30%.

7. REMIX-E

REMIX-E option assumes simplify fabrication of mixed fuel when using plutonium in high concentration together with enriched natural uranium. RepU is supposed to be enriched and used separately. This option may be an intermediate one and it provides the same level of SNF accumulation reduction as REMIX-B option.

In nuclear fuel cycle with REMIX-E 3 types of fuel are used: enriched natural uranium fuel NatU$_{En}$, RepU fuel and mixed NatU-Pu fuel. The fraction of mixed U-Pu fuel was reduced by increasing the initial concentration of plutonium to 5%, respectively, the volume of U-Pu fuel is “compressed”. It is important to note

that this NatU-Pu fuel includes enriched natural uranium (not RepU). Fabrication can be organized at the existing facilities for the MOX fuel fabrication plant at the MCC. Once reprocessed uranium is supposed to be used in current production in the form of $RepU_{En}$ fuel. Most of the fuel in this NFC is standard enriched natural uranium fuel.

The REMIX-E recycling schematic model is shown in Figure 5. The use of nuclear materials is shown in Figure 6. The rectangles indicate used fuel: from natural uranium, from mixed uranium-plutonium and from enriched reprocessed uranium ($RepU_{En}$). The arrows indicate excreted material after reprocessing and directed to fabricate a "fresh" fuel. The oval indicates unused regenerated nuclear material after reprocessing which is sent for storage. 7 cycles are estimated. The last cycle ends with spent fuel from the $RepU_{En}$ (highlighted by a dotted line), it is not transferred for reprocessing and taken for SNF. The amount of generated SNF is directly proportional to the duration of the cross-cycling and "compression" of fuel by plutonium and by limit of ^{232}U in RepU.

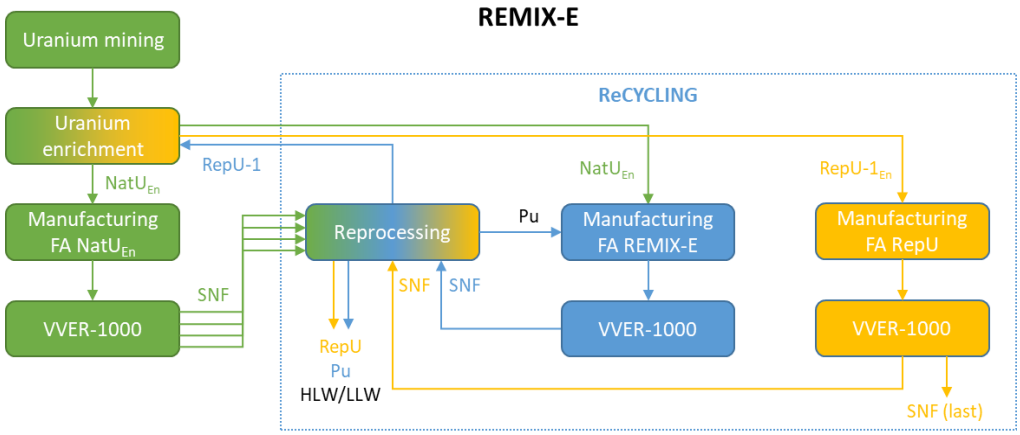


FIG. 5. REMIX-E recycling schematic model

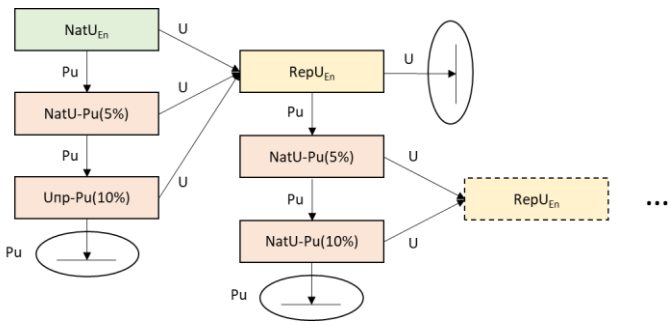


FIG. 6. The scheme of cross-use of nuclear materials

In option of cross-cycling shown in Figure 5–6, two cycles of mixed NatU-Pu fuel with "compression" are used. In the first cycle, there is a "compression" up to 5% Pu, in the second up to 10% Pu. The second (optional) Pu cycle is used only for the afterburning of plutonium when the number of odd isotopes of plutonium is almost equal to the number of even isotopes of plutonium. Despite the fact that the volume of spent nuclear fuel is reduced tenfold compared to open nuclear fuel cycle, a certain amount of burned-out reprocessed uranium is generated. Its energy potential is comparable to natural uranium.

8. REMIX-HET

There is an option dividing material flows during reprocessing to produce REMIX and uranium dioxide fuel separately. These two types of fuel in the end placed in a heterogeneous fuel assembly [10]. Such an approach allows to separate technological processes of production of hazardous REMIX fuel and relatively safe production of dioxide fuel. Figure 7 presents a schematic diagram of fuel rod placement in the fuel Assembly. The number of uranium-plutonium fuel rods in the FA depends of plutonium isotopic composition.

The content of plutonium and the number and arrangement of REMIX fuel rods in the FA is selected to ensure the same average burnup in the uranium and REMIX fuel rods. This approach makes it possible to obtain a balanced field of energy release during the entire fuel company. The spatial separation of enriched uranium and plutonium enhances the fission properties of FA due to less ^{235}U shielding as well as better fission of plutonium in the thermal spectrum. The content of plutonium in REMIX fuel rods is ~5% wt. which is almost 2 times less than the similar content of plutonium in MOX FA with the same burn-up parameters. The total content of plutonium in heterogeneous REMIX FA corresponds to its content in REMIX-A and REMIX-C. The irradiated uranium and uranium-plutonium fuel is mixed up in the recycling process. The isotopic composition of the mixture is close to REMIX-A/C variants and more than seven cycles can be provided.

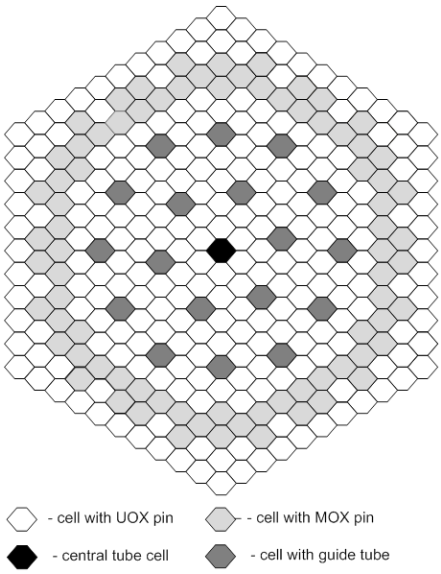


FIG. 7. Principal scheme of a heterogeneous FA for REMIX-Het.

Schematic diagram of the recycle process for REMIX-Het is presented in figure 8.

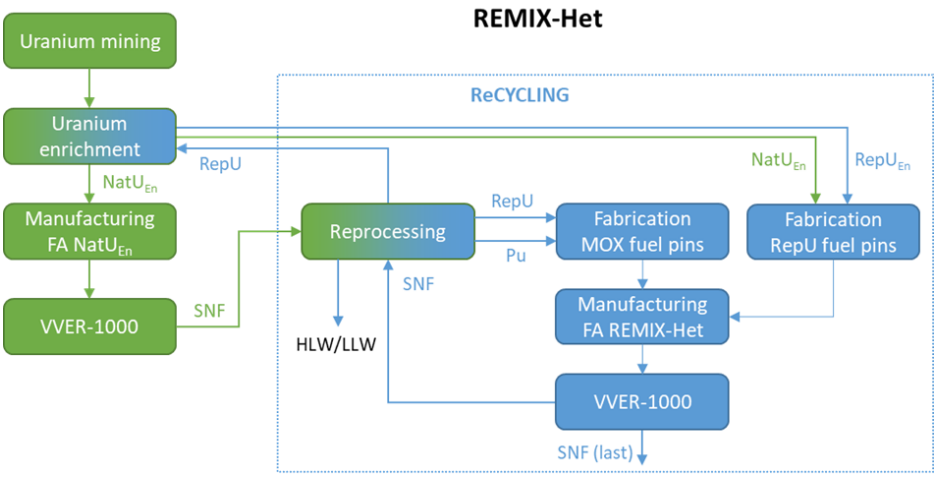


FIG. 8. REMIX-Het recycling schematic model.

9. COMPARATIVE ASSESSMENT OF THERMAL AND RADIATION CHARACTERISTICS OF FRESH AND SPENT REMIX FUEL OF DIFFERENT DESIGNS

Analysis of the estimated radiation characteristics of REMIX fuel before first irradiation cycle showed that its activity is several orders of magnitude higher than the activity of regular uranium dioxide fuel. In turn, among the different designs of FA with REMIX, REMIX-B and -E stands out, exceeding other options about 5 times due to the high content of plutonium while the activity of fresh REMIX-A, -C and-Het is practically the

same. In general, REMIX fuel activity slightly decreases with increase of storage time before irradiation. A similar situation is observed for heat release. The estimation of dose rates for fresh fuel showed that the REMIX-A and-C designs in this indicator are an order of magnitude higher than the regular UO_2. The dose rate from a REMIX-Het about 15% lower than the dose rate from REMIX-A and – C. REMIX-B and -E exceeds them about 70%.

Activities of different fuel designs during six cycles of irradiation increase. The most dramatic growth is on the second cycle compared to the first (~35%) for every REMIX fuel. Further difference is not so high and decreases from cycle to cycle due to reduction of the ^{241}Pu and ^{238}Pu accumulation rate.

The change in heat release even sharper between first and second cycles (~55%) but the downward trend is the same as for an activity (Figure 9). Similar situation is for the dose rates. Analysis showed that it is important to limit quantity of the ^{232}U in the repU because it affects the dose rates for fresh fuel significantly (Figure 10).

It should be noted that the number of cycles for REMIX-B/E are limited because of the heat release due to necessity of providing its value from one FA after irradiation and storage in pool on the level of 2 kW [11]. This requirement is dictated by the technical characteristics of the existing transport cask.

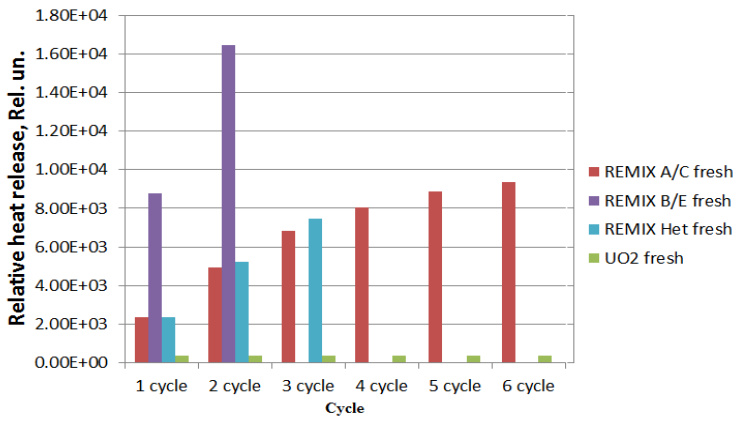


FIG. 9. Heat release of the fresh fuel during six cycles.

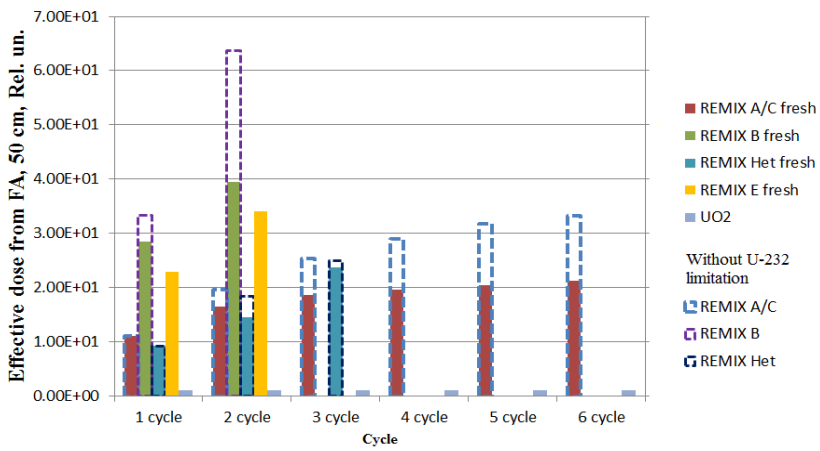


FIG 10. Dose rates of the fresh fuel during six cycles (50 cm from FA).

Analysis of the results showed that the activity of spent REMIX fuel increases compared to regular UO_2 fuel during storage after irradiation. This is due to the fact that at the beginning of storage interval activity is mainly determined by fission products which amounts depends on burnout and the same for all fuels. In the end of storage interval activity is determined by the content of ^{241}Pu and ^{238}Pu which accumulate the most in REMIX-B and -E. Similar situation is observed for heat release.

In our case dose rates are practically the same (Figure 11). However, it is necessary to pay attention to the spectra of the gamma radiation. The total intensity is determined by low-energy photons. Comparative analysis of the spectra for the considered fuel designs showed that the intensity of high-energy photons

(>5 MeV) for spent REMIX fuels is about an order of magnitude higher than for UO_2 fuel. In case of estimation dose rates from transport cask with SNF these photons will play a major role which will affect the difference between results for REMIX and UO_2 fuels. Although, the values of dose rates are increasing from cycle to cycle, their ratio between each other stays the same.

The activity of spent REMIX fuel increases from cycle to cycle compared to UO_2 fuel due to accumulation of plutonium but stays within reasonable limits. Changing in heat release have a similar character but difference between cycles are higher (Figure 12).

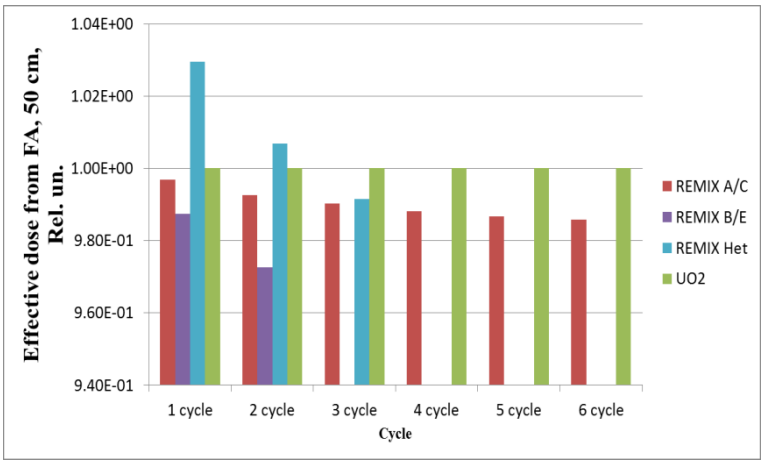


FIG. 11. Dose rates of the spent fuel after 5 years of storage during six cycles (50 cm from FA).

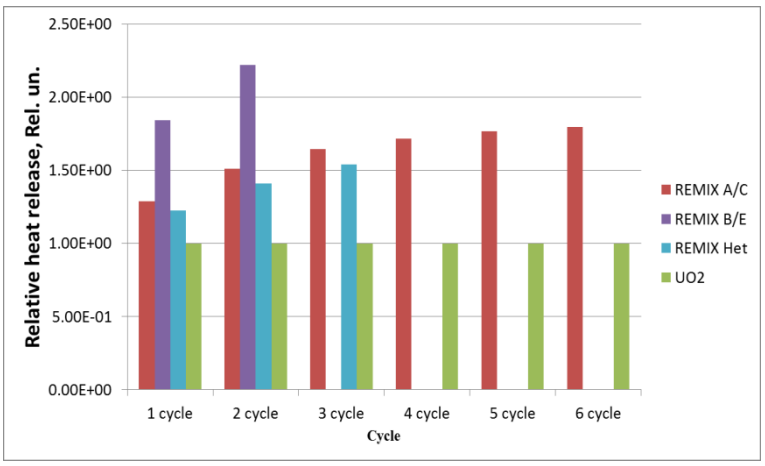


FIG. 12. Heat release of the spent fuel during six cycles.

10. THE ECONOMICAL ASPECTS OF REMIX FUEL MULTIPLE RECYCLING

The new technology implementation should be considered from the economic point of view. It is important to compare results with the open fuel cycle for UOX fuel with SNF long-term storage and final disposal option. Comparative evaluation of fuel cycle options for the VVER-1000/1200 core in the transition to REMIX fuel is carried out by analysing the economic parameter of fuel cost component (FCC). The main comparison was prepared for reactors of the same type operating under the same scenario conditions.

Fuel cycle costs selected in the investigation for different stages of fuel cycle are taken from different sources [12–14] applied to the Russian infrastructure basis. The additional calculation parameters were chosen: 3% discount rate, 7 years of SNF storage before reprocessing for REMIX fuel and 60 years storage before final disposal for opened fuel cycle with UOX fuel.

The resulting comparison of economical investigation presented in the Table I. The reprocessing stage will be identical for all variants of REMIX fuel implementation because the same burnup conditions are chosen and the same SNF values are to be reprocessed.

TABLE 1. THE COMPARISON OF PHYSICAL AND ECONOMIC INDICATORS FOR REMIX/UOX FUEL IN VVER-1000/1200

	Recycle №	Natural U savings Δ, %	SWU savings Δ, %	Fuel cost component, c/kWt h			
				Frontend	Backend	Total	Δ, %
UOX		0	0	0.34	0.07	0.41	0
REMIX-	1	31.91	18.95	0.32	0.08	0.40	4.4
A/C	6	30.29	10.05	0.33	0.08	0.41	1.3
REMIX-	1	31.86	17.97	0.29	0.08	0.37	10.5
Het	6	34.03	16.66	0.28	0.08	0.37	10.3
REMIX-	1	33.46	29.97	0.30	0.08	0.38	7.7
B/E	3	47.97	31.95	0.28	0.08	0.36	13.3

Comparison of the results shows that the use of REMIX fuel reduces the rate of FCC. The involvement of not only regenerated uranium, but also plutonium in the fuel cycle made it possible to achieve significant savings in both the consumption of natural uranium and the amount of SWU.

The savings of natural uranium and SWU for REMIX-Het are comparable to the results obtained for REMIX-A/C technology. The comparison of indicators for the scenario with REMIX-B/E fuel with previously considered options shows significant savings of natural uranium and SWU, which reduces the rate of FCC. It should be taken into account that the balance of nuclear materials limits the share of reactors that can be loaded with REMIX-B/E fuel in the system.

11. CONCLUSIONS

The proposed above approach to the REMIX-fuel technology has potential to improve the energy potential using of the remaining uranium and accumulated plutonium, to eliminate the long term storage of SNF and products of reprocessing for nuclear fuel cycle of thermal reactors. The five options of REMIX FA fuel cycle proposed in the paper. All considered variants assume Pu multiple recycling. The Pu content and isotopic quality in the fuel matrix stabilized with growth of recycle number for the most variants. The regenerated materials usage in thermal power reactors gives up to 35% saving of natural uranium consumption.

Estimation of technical and economic assessment presented in the paper has demonstrated that the use of REMIX technology in the closed fuel cycle is less expensive than the open fuel cycle.

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