Possibilities and Features of REMIX Technology as an Initial Stage in the Establishing of a Full-Scale Two-Component Nuclear Energy System

E R Sitdikov, A V Vasilenko and A I Diachenko
Rosatom Technical Academy, 249031, Kaluga region, Obninsk, Kurchator str., 21
E-mail: emilsitdikov@gmail.com

Abstract. According to the Energy Strategy of Russia for the period up to 2035, the direction of the transition of the nuclear industry is to be headed to a two-component nuclear energy system (NES). In this paper, in order to identify the features of recycling MOX and REMIX fuel and to analyze possible strategies for two-component NES, the changes in the isotopic composition of the plutonium fraction during multiple recycling of fuel has been evaluated, and the consumption of plutonium in various strategies of establishing a two-component NES has been quantitatively assessed. The data obtained can be used for the further analysis of the possibility of developing the two-component NES concept with the involvement of REMIX fuel in the nuclear fuel cycle of thermal reactors at the initial stage of the establishing of a full-scale two-component NES.

1. Introduction
According to the Energy Strategy of Russia for the period up to 2035, the key challenges facing ROSATOM State Atomic Energy Corporation are to form a new technological platform for nuclear power with NPPs on improved water-cooled and fast neutron reactors operating in a closed nuclear fuel cycle, and to increase the export potential of Russian nuclear technologies, as well as the further development of the export of NPPs, nuclear fuel and electricity [1].

In support of the development of a full-scale two-component nuclear power program, Rosenergoatom JSC is currently implementing a project focused on optimizing a two-component NES based on the use of VVER and BN reactors together. The key feature of this project is a two-stage programme for development of a two-component NES [2].

The first stage of development of a two-component NES is related to the setting up the pilot-industrial power complexes with BN and VVER reactors, that involves R&D on all parts of a two-component NES, including development of plutonium-based fuel and obtaining a license to operate MOX fuel in VVER reactors. In support of this stage, a pilot line for the production of MOX fuel for the BN-800 reactor has been set up, and the first batch of 18 fuel assemblies with MOX fuel has been delivered and loaded to Beloyarsk NPP [3]. Along with this, the Mining and Chemical Combine has already manufactured 169 MOX fuel assemblies with for the BN-800 reactor (2020) [4].

At the same time, it should be noted that in parallel since 2016 SSC RIAR has been conducting research on an innovative REMIX fuel based on the concept of multiple recycling of reprocessed uranium and plutonium [5], and tests of REMIX fuel in the third fuel cycle at the Balakovo NPP are continuing [6].

Further development of the national two-component NES (the second stage) is associated with the solution of such issues as:
• development of facilities and achievement of industrial scale for closed nuclear fuel cycle, and serial operation of BN reactors,
• increasing the level of safety, economics of a two-component NES,
• development of new generation reactors,
• solving the issues of spent nuclear fuel accumulation and radioactive waste management.

At the same time, according to the Energy Strategy of Russia for the period up to 2035, the commissioning of new generating capacities based on fast reactors with a sodium coolant is postponed at least until 2035. This may be one of the key constraints to the establishing of a full-scale two-component NES. Thus, under current conditions, considering the ongoing tests of REMIX fuel in the VVER reactor, and the needs of foreign recipient countries of Russian energy technologies in resolving the issue of spent nuclear fuel management and taking into account the Energy Strategy in terms of commissioning new units with fast neutron reactors REMIX fuel may have a number of preferences at the initial stage of the formation of a two-component NES [7-11].

2. Modeling of the isotopic composition of spent fuel

One of the necessary stages of this study was to analyze the change in the isotopic composition of plutonium during multiple recycling of plutonium-based fuels in order to identify the features of their use in the establishing of a two-component NES based on the joint use of pressurized water reactors and fast reactors with sodium coolant.

2.1. Recycling strategies

Table 1 below specifies the sequence of recycling plutonium-based fuels considered in this study in VVER-1200 and BN-800 reactor facilities, where:

- “MOX” - recycling of MOX fuel,
- “MOX-WG” - recycling of MOX fuel with the involvement of ex-weapons-grade plutonium,
- “REMIX 1” - recycling of REMIX fuel,
- “REMIX 2” - recycling of REMX fuel with "purification" of plutonium fraction in a fast reactor.

At each recycle, after spent nuclear fuel reprocessing minor actinides are sent for long-term storage, and in the MOX fuel recycling sequence, reprocessed uranium is also sent for storage. Enriched natural uranium with a $^{235}\text{U}$ isotope content of 16% is used as the feed material for the formation of REMIX fuel of equivalent enrichment.

| No. of recycle | “MOX” | “MOX –WG” | “REMIX 1” | “REMIX 2” |
|---------------|-------|-----------|-----------|-----------|
| 1             | VVER  | (MOX with (UOX fuel)) | VVER (UOX fuel) | VVER (UOX fuel) |
| 2             | BN    | BN        | VVER      | VVER      |
| 3             | VVER  | VVER      | VVER      | BN        |
| 4             | BN    | BN        | VVER      | VVER      |
| 5             | VVER  | VVER      | VVER      | BN        |
| 6             | -     | -         | -         | VVER      |

In the present study, the analysis of the neutron multiplication properties of the fuel as well as the characteristics of the isotopic composition of the spent fuel were carried out in the unit cell approximation using the SERPENT 1.1.7 code, which implements the Monte Carlo method. This software package is developed by VTT Technical Research Center of Finland and is used in more than 100 universities and research organizations around the world [12].
The SERPENT code is a certified software tool, and it has a certificate issued by the SEC NRS valid until 16.12.2025, which means the possibility of using for calculating $K_{\text{inf}}$ of the systems with nuclear fuel and nuclear fissile materials [13].

Table 2 below indicates the characteristics of the fuel cells used in the estimations. The characteristics of the unit cells of the fuel assemblies (FA) of VVER-1200 and BN-800 are selected as the reference data.

Table 2. Unit cells characteristics of VVER-1200 and BN-800 reactor facilities

| Characteristics, measure unit | VVER-1200 | BN-800 |
|-------------------------------|-----------|--------|
| Fuel cladding external diameter, mm | 9,1 | 6,9 |
| Fuel cladding material          | Alloy E-110 (Zr + 1% Nb) | ChS-68HD |
| Fuel pin external diameter, mm   | 7,6 | 6,1 |
| Fuel pin central hole diameter, mm | 1,2 | - |
| Fuel rod pitch, mm              | 12,75 | 7,95 |
| Fuel enrichment, %              | 4,95 | 20 |
| Fuel density, g/cm³             | 10,5 | 10,5 |
| Power density, kW/kg            | 36,8 | 107,2 |
| Estimated burnup range, MWd/kg  | 55 | 66 |
| Coolant density, g/cm³          | 0,7278 | 0,84 |

2.2. $K_{\text{inf}}$ behaviour during multiple sequential fuel recycling

Figures 1-2 show the dependence of the infinite neutron multiplication factor of the VVER-1200 cell lattice for different strategies of MOX and REMIX fuel recycling (table 1) depending on the burnup.

As the result of the accumulation of non-fissile isotopes of uranium and plutonium the condition of equivalent enrichment must be met during the arrangement of fuel load for each subsequent cycle, i.e. the fuel should have multiplying characteristics similar to fresh uranium oxide fuel.

During sequential recycling of MOX and REMIX fuel, the value of the neutron multiplication factor decreases depending on the recycle number, which is due to the involvement in the fuel cycle of plutonium isotopes with large neutron-absorption cross sections in comparison with uranium isotopes.

In the case of recycling MOX fuel with the involvement of ex-weapon-grade plutonium, the effect is higher than in the case of recycling MOX fuel based on reactor plutonium. For the case of recycling REMIX fuel, it was shown that each subsequent recycle makes a smaller contribution to the decrease in $K_{\text{inf}}$.

In all the considered recycling strategies, the calculated isotopic composition of the fuel makes it possible to achieve the required burnup, i.e. the condition of equivalent enrichment is satisfied. Equivalent characteristics of MOX fuel were achieved by trial and error method of the required fractions of plutonium and depleted uranium. The formation of the equivalent characteristics of REMIX fuel was carried out using the equation given in [14].
2.3. Evolution of plutonium fraction isotopic vector

Figures 3 and 4 show the evolution of the plutonium fraction isotopic vector in different fuel recycling sequences, which is expressed as a change in the ratio of the fractions of odd plutonium isotopes ($^{239}$Pu, $^{241}$Pu) to the total plutonium concentration in the discharged fuel.

The results presented in figure 4 indicate that the change in the isotopic composition of plutonium in the process of multiple recycling of REMIX fuel in VVER-1200 compared to MOX fuel stabilizes after the second recycle and there is no significant degradation in terms of energy potential for thermal reactors. Also, it should be noted that the involvement of the BN-800 reactor in the recycling sequence has a positive effect on the fissile properties of the fuel.

The opposite effect is observed when ex-weapon-grade plutonium is included in the MOX fuel cycle - the change in the fraction of fissile plutonium isotopes occurs abruptly, which indicates a high degree of degradation of the plutonium fraction isotopic composition.

Figure 3. Change in the total fraction of odd plutonium isotopes in MOX fuel at the end of the cycle.

Figure 4. Change in the total fraction of odd plutonium isotopes in REMIX fuel at the end of the cycle.
Figure 5. Change in the fraction of $^{238}$Pu in the Pu composition of the MOX fuel at the end of the cycle.

In addition to considering the change in the fraction of $^{239}$Pu and $^{241}$Pu, it is especially important to take into account the effect of $^{238}$Pu accumulation, since an increase in the fraction of this isotope leads to an increased heat release of the fuel.

When recycling MOX fuel using the “MOX” sequence, the $^{238}$Pu accumulation is stabilized at the range of 2-3% of the total plutonium fraction (figure 5). Also, it should be noted that by the 5th recycle the composition of MOX fuel according to the “MOX-WG” sequence with the involvement of ex-weapon-grade plutonium is close to the composition of traditional MOX fuel (based on reactor-grade plutonium) and the accumulation of $^{238}$Pu is about the same level.

In the case of recycling REMIX fuel according to the “REMIX 1” sequence, the fraction of $^{238}$Pu increases with each subsequent recycling, which will bring difficulties in handling the fuel (figure 6). The inclusion of the BN-800 reactor in the “REMIX 2” sequence makes it possible to reduce the $^{238}$Pu fraction by 1.7 times (at the 6th recycle) and stabilize it at the range of 3-5%, thus positively affecting on the fissile properties of the REMIX fuel in thermal reactors.

3. Nuclear fuel consumption in NPPs in a two-component NES

The results presented above show that considering less degree of reduction in the multiplication properties and less accumulation of $^{238}$Pu the most acceptable options are the “MOX” fuel recycling sequence using traditional MOX fuel and the “REMIX 2” sequence using REMIX fuel with intermediate “purification” of plutonium fraction in BN reactor (table 1).

In order to assess the plutonium consumption in thermal and fast reactors, the analysis of plutonium loading and discharging in the “MOX” and “REMIX 2” sequences was carried out. The results are shown in figures 7 and 8.
Based on the analysis of the plutonium consumption in VVER-1200 and BN-800 reactors, several specific features can be identified. When the VVER-1200 reactor is refueled (figure 7), up to ~0.28 t/year of plutonium can be discharged, while to load BN-800 reactor with fuel based on MOX (cycle No. 2) ~2.09 t/year of plutonium is required. To ensure the subsequent recycling (No. 3) in the VVER-1200 reactor MOX fuel with a quality corresponding to that discharged from the BN-800 reactor (~2.16 t/year after cycle No. 2) ~0.406 t/year of plutonium is required. Accordingly, to form a full load of the BN-800 reactor based on MOX fuel, the required amount of plutonium can be discharged from 7 VVER-1200 reactors, and the amount of plutonium discharged from the BN-800 reactor can provide up to 5 VVER-1200 reactors, i.e. in a nuclear power plant with a MOX fuel recycling sequence, up to 12 VVER-1200 units can be involved for each BN-800 unit in operation at the initial stages of fuel recycling (figure 9).

In turn, in the “REMIX 2” recycling sequence the fuel is subsequently irradiated in a VVER-1200 reactor. At the same time, according to the results obtained and shown in figure 8 the amount of discharged plutonium is about ~0.28 t/year, which is sufficient to form the next VVER-1200 load with REMIX fuel (~0.214 t/year at the beginning of cycle No. 2). The next stage is the “purification” of the fuel in the BN-800 reactor, i.e. improvement of the plutonium isotopic vector in terms of its energy potential in thermal reactors. To ensure the full load (No. 3) of the BN-800 reactor, ~2.16 t/year of plutonium is required. The fissile properties of discharged plutonium (~2.22 t/year after cycle No. 3) are sufficient to form a load with REMIX fuel in VVER-1200 with a demand of ~0.285 t/year.

Accordingly, to form a full load of BN-800 in the “REMIX 2” sequence, it is necessary to discharge and reprocess fuel from 6 VVER-1200 reactors (from cycle No. 2). Fuel “purified” in BN-800 reactor (cycle No. 3) can provide up to 8 VVER-1200 units (cycle No. 4) in the next cycle.

Thus, in a NES with a REMIX fuel recycling sequence with intermediate “purification” in BN-800 reactor, up to 20 VVER-1200 units can be involved for each BN-800 unit in operation at the initial stages of fuel recycling (figure 10).
4. Conclusion

Analysis of the change in the plutonium fraction isotopic vector in the process of multiple recycling of REMIX fuel in VVER-1200 compared to MOX fuel indicates that the composition of plutonium stabilizes after the second recycle and there is no significant degradation in terms of the energy potential for thermal reactors.

An assessment of plutonium consumption in thermal and fast reactors with recycling strategies using traditional MOX fuel and REMIX fuel with intermediate “purification” in the BN reactor showed that the use of REMIX fuel at the initial stage of the transition to a two-component NES can allow a larger number of VVER reactors to be involved in the cycle for each BN reactor operated, which is an advantage in conditions of the high cost of BN technology.

One of the possible option to settle the issue related to $^{238}$Pu accumulation could be the inclusion of fast reactors in the recycling sequence, and the “purification” of the plutonium fraction in the fast BN spectrum, similar to the MOX fuel recycling sequence.

The use of ex-weapon-grade plutonium for the fabrication of MOX fuel at the moment seems inappropriate due to factor such as degradation of the plutonium isotope vector in MOX fuel cycles. It is more expedient to analyze the option of using ex-weapon-grade plutonium as a feed material for the formation of fuel.

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