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Research Article

Evaluation of neutronic performance for the VVER-1000 reactor core with regenerated uranium-plutonium fuel*

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Abstract

The possibility has been considered for the VVER-1000 reactor fuel loading to be formed based on regenerated fuel with the use of the spent fuel accumulated in reactors of the same type. A study was undertaken to investigate the change in the isotopic composition of the plutonium discharged from a thermal reactor in the course of its multiple reprocessing and recycle in a thermal neutron reactor. To obtain an equilibrium isotopic composition of the reactor-grade plutonium, 3D neutronic calculations were performed for the stationary fuel cycles of a VVER-1000 serial reactor with conventional oxide fuel and oxide fuel based on regenerated uranium and based on an undivided mixture of uranium and plutonium oxides from SNF. The neutronic performance of reactor cores was compared for the above mentioned fuel types in the course of the fuel company, including the following: in-core radial power density shaping, values of reactivity coefficients for various thermal parameters, reactivity control system efficiency, etc.

Keywords

neutronic calculation, reactor core, VVER, REMIX fuel, SAPPHIRE, DESNA, closed nuclear fuel cycle, plutonium, uranium regenerate

Introduction

Currently, no comprehensive solution has been found worldwide to the problem of storing and handling the SNF accumulated in the process of the power reactor operation. Some 10 thousand tons of SNF is unloaded annually from reactors (Andrianova et al. 2015; Davidenko and Tsibul'skii 2015), of which about 2 thousand tons is reprocessed. The major SNF reprocessing countries are France where a part of the plutonium generated in PWR and BWR reactors is used for the PWR fuel fabrication (Grouiller et al. 2003), Japan and Russian Federation where regenerated uranium from VVER-type reactors is used to produce fuel for RBMK-1000 reactors (Fedorov et al. 2005). The RT-1 plant's capacity is enough to reprocess some 400 tons of nuclear fuel annually (Adamov et al. 2021). Most of the power reactor operating countries either treat SNF as the fuel cycle end product (the USA, Finland) and are considering, accordingly, its final disposal in geological formations, or postpone the solution of the SNF accumulation and handling problem for an indefinite period while keeping it in onsite storages.

It is possible to reduce the amounts of the SNF accumulated in the course of the power reactor operation through its reprocessing and involvement in the fuel cycle, this to allow expanding the current raw material base.

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Effective methods for multiple recycle of regenerated fuel in VVER-type reactors will make it also possible to reduce the consumption of natural uranium in fabrication of fuel and cut the quantities of radioactive waste to be permanently disposed. Given the time required for the large-scale commissioning of fast neutron reactors, the plutonium recycle in the thermal neutron reactor cores will allow time for the evolution of fast neutron reactor technologies and their integration in the two-component nuclear power.

This paper considers an option with closing a fuel cycle based only on thermal neutron reactors and multiple recycle of spent nuclear fuel in an NPP with a VVER-1000 reactor by the example of a stationary fuel loading. The FA arrangement in the core was adopted in accordance with Semchenkov 2014. The study was conducted for two fuel cycles: a fuel cycle with REMIX fuel, which uses an unseparated mixture of uranium and plutonium oxides from unloaded fuel, and a fuel cycle based on regenerated uranium additionally enriched with ^{235}U. It was assumed for the calculations that fuel was fully purified of fission products and minor actinides. The neutronic cross-section libraries were calculated using the SAPPFIRE-95 code (Tebin et al. 1985; Karpov and Tebin 1997), and the core neutronics was calculated based on a 3D two-group neutron and thermal-hydraulic core module, DESNA, which is a part of the Rainbow-TPP code (Kavun 1999). As part of justifying the possibility for using REMIX fuel in thermal neutron reactors, individual experimental FAs with REMIX fuel elements were installed at the Balakovo NPP. For the neutronic studies, this paper considered a VVER-1000 reactor with a core fully composed of FAs with fuel based on regenerated uranium or based on unseparated uranium-plutonium mixture.

To investigate stationary fuel cycles with the core 100% loaded with regenerated fuel, a study was undertaken into the change in the isotopic composition of fuel, if multiply recycled, for the purpose of obtaining equilibrium concentrations of plutonium isotopes in the fuel used (Semishin and Kavun 2019). To determine the REMIX fuel composition in the steady fuel cycle, the change in the content of plutonium isotopes in fuel was investigated depending on the number of recycles. The change in the isotopic composition of plutonium is presented in Fig. 1. After 18 recycles, the isotopic composition of unloaded fuel changes in the estimated error limits, so it was taken as the equilibrium composition of reprocessed fuel. This number of recycles needs to be calculated since the concentration of ^{238}Pu in unloaded fuel continues to grow noticeably even after five recycles. One of the objectives pursued in this paper is to show that even in the event of continuous spent fuel recycle in VVER-type reactors with the least favorable isotopic composition of plutonium, which corresponds to the equilibrium composition of high-absorbing isotopes, and the core being fully loaded with such fuel, its neutronics allows achieving a performance comparable with that for uranium fuel. With normally considered three to five recycles, the isotopic composition of fuel is more favorable.

Reprocessed plutonium contains high thermal neutron absorbing plutonium isotopes ^{238}Pu and ^{240}Pu. In the process of the fuel recycle, the concentration of the ^{240}Pu isotope

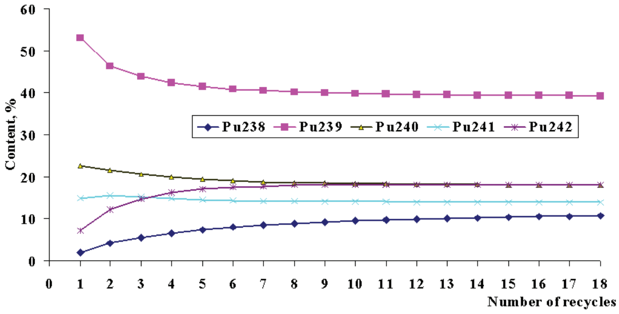

Figure 1. Variation in the isotopic composition of plutonium for multiple recycle.

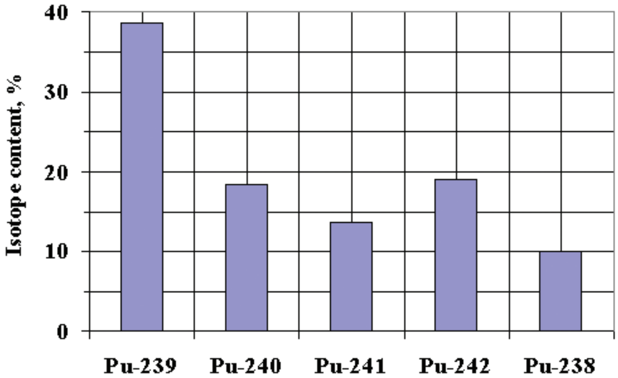

Figure 2. Equilibrium isotopic composition of plutonium in REMIX fuel.

reaches an equilibrium value and does not further practically vary in the course of recycle, but the concentration of the ^{238}Pu isotope continues to grow even after a large number of recycles. This will require a gradual increase in the fissile isotope enrichment to make up for the parasitic absorption and the increase in the fuel consumption during multiple recycles. Apart from the deterioration in the multiplying properties of fuel, the presence of ^{238}Pu leads to increased activity and heat deposition as compared with fresh uranium fuel. This leads to the need for handling unburnt assemblies in the same way as spent assemblies, which complicates the process operations for reactor refueling and fuel transportation from the FA manufacturer to the plant site. Consideration is further given to the stationary fuel cycle occurring in about 30 years after the transition to the REMIX fuel loading starts. The equilibrium REMIX fuel composition used for further calculations is presented in Fig. 2.

The transition to fuel loadings using regenerated fuel comprised three stages for the gradual replacement of all FAs with uranium fuel for FAs with regenerated fuel in accordance with the stationary refueling patterns. No characteristics of transitional loadings or refueling pattern optimizations were considered. The design fuel cycle duration of regenerated fuel was preserved by varying the REMIX fuel additional enrichment with the ^{235}U fissile isotope to make up for the content of ^{236}U, ^{238}Pu and ^{240}Pu. Therefore, the stationary composition of fuel for a REMIX fuel cycle is as follows:

- 5.85% ^{235}U + 1.2%$^{(239+241)}$ Pu for FAs with an average enrichment of 4.9%;

- 5.25% ^{235}U + 1.2%$^{(239+241)}$Pu for FAs with an average enrichment of 4.4%.

The required ^{235}U enrichment was also selected for the fuel based on additionally enriched regenerated uranium to make up for the content of the ^{236}U isotope and to preserve the design fuel cycle duration (Proselkov et al. 2003). The required enrichment was:

- 5.2% ^{235}U for FAs with an average enrichment of 4.9%;
- 4.6% ^{235}U for FAs with an average enrichment of 4.4%.

A neutronic calculation for stationary fuel cycles has shown that a higher BOC concentration of boric acid than for uranium fuel is required to preserve the fuel cycle duration when regenerated fuel or REMIX fuel is used. Table 1 presents critical values of the boric acid concentration for the minimum controlled reactor power, the nominal power level and the shutdown concentration of boric acid.

Table 1. Concentration of boric acid in coolant for different operating modes

Parameter	Value		
	Uranium fuel	**REMIX fuel**	**Regenerated uranium**
C_{H3BO3} (t = 0 days, N = 1000 MW), g/kg	7.7	9.2	8.0
C_{H3BO3} (t = 0 days, N = 0 MW), g/kg	11.9	16.6	12.5
C_{H3BO3} (shutdown), g/kg	<16	20.5	14.5

The power density distribution calculation has shown that no maximum power distribution peaking takes place in the course of the fuel cycle when REMIX or regenerated fuel is used, as compared with the design fuel cycle. In the event of a REMIX fuel cycle, there is a decrease observed in the maximum power distribution peaking change as compared with standard fuel and fuel based on regenerated uranium. For standard fuel and fuel based on regenerated uranium, the maximum power peaking factor is 1.35, while it is equal to 1.26 for the REMIX fuel inventory. It was assumed for the calculation of fuel loadings with regenerated uranium that the gadolinium fuel rod arrangement in FAs is the same as in uranium fuel loadings. The BOC and EOC relative power distribution for the fuel cycles under investigation is presented in Figs 3 and 4 where a symmetry sector of 30° is provided for illustration.

All reactivity coefficients for fuel loadings with REMIX fuel and fuel based on regenerated uranium meet the requirements set forth in the Annex to the Nuclear Safety Rules for Nuclear Power Plants (NP-082-07). The variation in the reactivity coefficients in the course of the fuel cycle for a reactor at the rated power level is presented in Figs 5 and 6. The values of the fuel temperature reactivity coefficient, the cumulative temperature reactivity coefficient, and the coolant specific volume reactivity coefficient are negative throughout the fuel cycle.

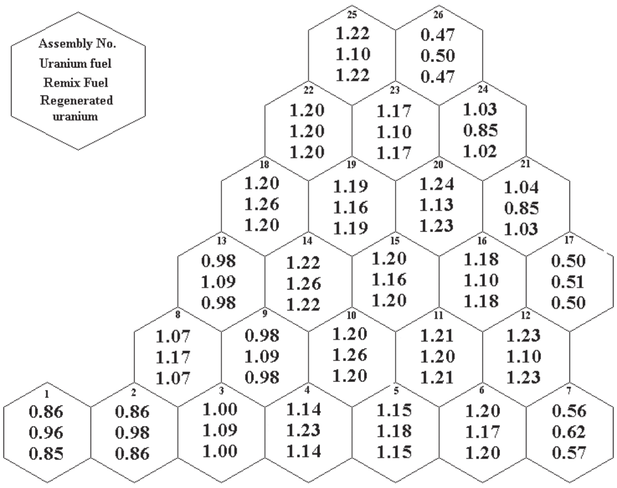

Figure 3. BOC relative assembly power density distribution.

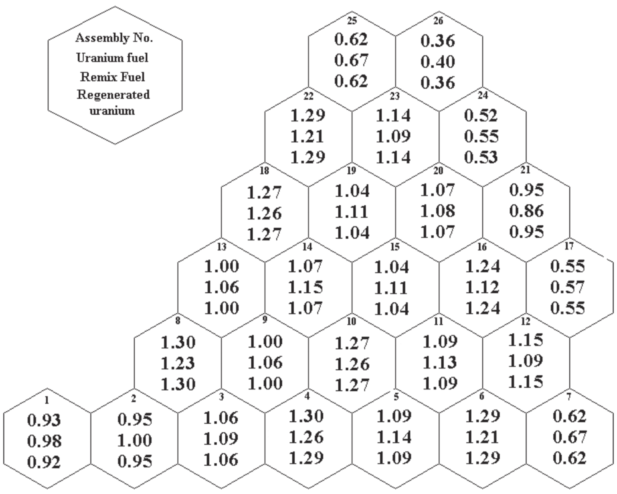

Figure 4. EOC relative assembly power density distribution.

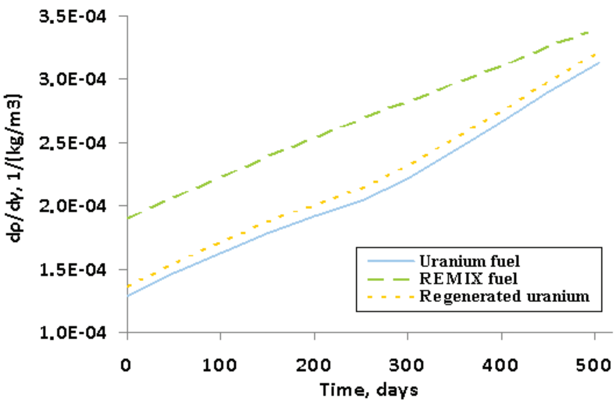

Figure 5. Variation in the coolant density reactivity coefficient.

When REMIX fuel cycles are used, there is an increase observed in the absolute values of the fuel temperature, coolant density and total temperature reactivity coefficients, which increases, consequently, the re-criticality temperature. The variation in the fuel cycle re-criticality temperature for the fuel cycles under consideration is presented in Fig. 7.

Apart from the growth in the re-criticality temperature, the possibility for re-criticality to occur for the REMIX fuel cycle under investigation exists from the very

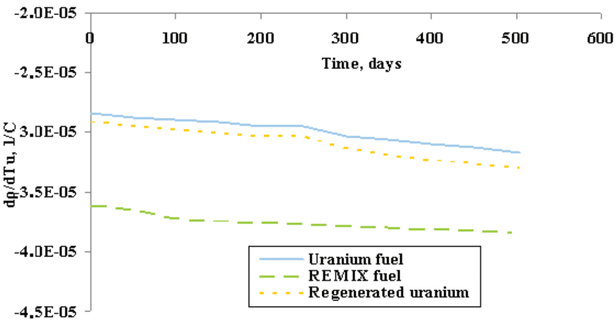

Figure 6. Variation in the fuel temperature reactivity coefficient.

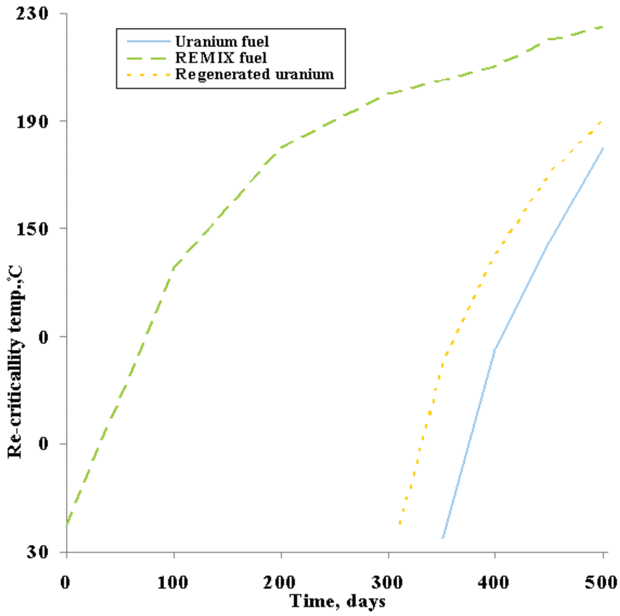

Figure 7. Variation in the re-criticality temperature.

beginning of the fuel life, while re-criticality is possible for standard fuel only after 350 effective days.

Calculations of the integral efficiency for the CPS rod and scram control group have shown that the scram efficiency decreases, as compared with standard fuel, when REMIX fuel is used. The BOC and EOC integral efficiency

Table 2. Control group integral efficiencies

Parameter	Value		
	Uranium fuel	REMIX fuel	Regenerated uranium
Control group BOC integral efficiency, %			
- $N = 0$ MW	0.684	0.638	0.683
- $N = 1000$ MW	0.712	0.629	0.707
Control group EOC integral efficiency, %			
- $N = 0$ MW	0.627	0.628	0.624
- $N = 1000$ MW	0.615	0.593	0.611

Table 3. Scram integral efficiencies

Parameter	Value		
	Uranium fuel	REMIX fuel	Regenerated uranium
Scram BOC integral efficiency, %			
- $N = 0$ MW	7.44	5.91	7.35
- $N = 1000$ MW	7.55	6.05	7.46
Scram EOC integral efficiency, %			
- $N = 0$ MW	7.08	6.09	7.04
- $N = 1000$ MW	7.23	6.28	7.19

values of the CPS rod and scram control group for a reactor at the rated power level and the minimum controlled reactor power level are presented in Tables 2 and 3.

Achieving the design efficiency value for the CPS rod and scram control group requires using ^{10}B-enriched boron carbide in the CPS absorber rods or a larger number of control rods. The VVER-1200 reactor CPS rod arrangement can be used for REMIX fuel inventories. No decrease in the CPS rod efficiency is observed in the event of regenerated uranium based fuel.

The potential cause for a decrease in the integral efficiency of control rods, when REMIX fuel is used, is a harder neutron spectrum as compared with fuel based on enriched uranium. The neutron spectra calculations in a 26-group approximation for FAs with a 4.4% enrichment have shown an increase in the fast neutron fraction in groups 1 through 11 and a decrease in the thermal neutron fraction in group 26 (Fig. 8).

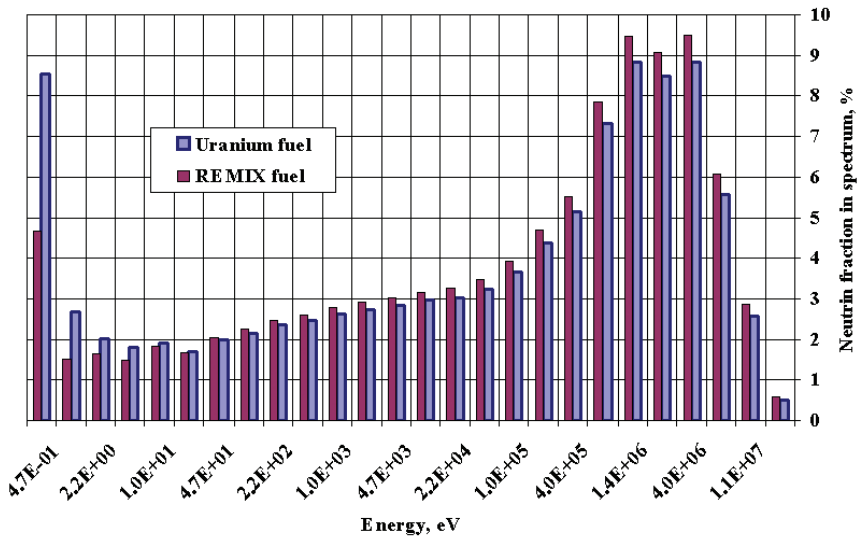

Figure 8. Neutron spectra for FAs with a 4.4% enrichment.

The calculation for the REMIX fuel cycle suggests that it is possible to use a core fully loaded with REMIX fuel provided boron carbide and boric acid with a higher ^{10}B enrichment are used respectively in absorber rods and in coolant to satisfy the nuclear safety requirements and meet the core parameters when enriched uranium based fuel is used (Pavlovichev et al. 2006, 2008). Using such fuel cycle will make it possible to save about 30% of uranium (Bobrov 2016) and avoid storage of plutonium obtained in VVER-type reactors. The calculation of a regenerated uranium fuel cycle has shown that it is possible to use a core fully loaded with regenerated fuel. Using a fuel cycle based on regenerated uranium does not require any changes in the CPS absorber rods and the coolant water chemistry since it has little effect on the core's neutronic parameters.

Conclusions

It has been shown that it is possible to get the SNF withdrawn from thermal neutron reactors involved in the nuclear fuel cycle for similar reactors, specifically for VVER-1000 (V-320) reactors. The fuel cycle considered suggests long-term operation of facilities (for about 50 years) in a closed cycle with multiple recycle of spent fuel since unloaded fuel was assumed to have an equilibrium composition in calculations with the least favorable isotopic composition of plutonium. The neutronic properties of the core fully loaded with regenerated fuel make it possible to achieve the same fuel cycle duration as for fuel based on regenerated uranium. Calculations of reactivity coefficients have shown that using the loadings under consideration leads to an increase in their absolute value, this causing an increase in the re-criticality temperature. Its EOC value is 225 °C. Apart from this, a lower value of the cycle maximum power peaking factor for plutonium fuel allows one to suggest that using such fuel makes it possible to reduce or give up the use of gadolinium fuel elements in the event of an increased ^{10}B content in coolant since a change in the neutron spectrum leads to their reduced efficiency.

Using fuel based on regenerated uranium allows expanding the fuel base for VVER-type reactors and does not require making changes to the CPS absorber rods and the coolant water chemistry. However, using this fuel fails to solve the problem of storing and using plutonium generated in VVER-type reactors.

Using a fuel cycle with regenerated REMIX fuel makes it possible to save as much natural uranium as possible, as well as to abandon long-term storage of plutonium produced in VVER-type reactors. Since all of the unseparated mixture of uranium and plutonium isotopes from spent fuel is used for the REMIX fuel fabrication, there is a smaller risk of unauthorized plutonium proliferation. However, using a core with a 100% REMIX fuel inventory places tougher requirements for the CPS absorber rods due to a generally harder neutron spectrum and requires using a ^{10}B-enriched boric acid solution in coolant.

The investigated fuel cycles can be viewed as intermediate solutions for the nuclear power transition to a two-component basis using both fast and thermal reactors for as efficient disposal of fuel resources as possible (Adamov et al. 2021).

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