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Research Article

Physical feasibility of minor actinides transmutation in a two-component nuclear energy system in Russia

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Abstract

A transition to a two-component nuclear power structure with a reactor fleet consisting of thermal and fast reactors as envisioned in the Russian nuclear power development strategy to 2050 and outlook to 2100 will require optimal spent nuclear fuel and radioactive waste management solutions. A core issue in this regard is managing the long-lived minor actinide (MA) inventory that affects overall nuclear power ecological safety. The study examines several options for homogenous MA (Am and Np) transmutation using modern calculation codes with MA transmutation rate and material balances taken into account. Results demonstrate that if fast reactor installed capacity reaches 92 GWe by 2100 there would not be any need for dedicated MA-burners as the MA issue would be gradually resolved within the two-component nuclear energy system by the end of the century.

Keywords

Fast reactor, Nitride fuel, spent nuclear fuel, minor actinides, transmutation, two-component nuclear energy system

Introduction

Many industry experts consider using closed nuclear fuel cycle (NFC) and fast reactor technologies as a means to resolving spent nuclear fuel (SNF) and radioactive waste management issues that hinder nuclear power development. A major problem for the nuclear industry today is minor actinide (MA) accumulation. MA affect overall nuclear power ecological safety for periods that the scientific and public community consider historically significant. Currently there is no consensus on the most desirable option for MA transmutation. Some experts even propose using dedicated MA burner reactors, which would further strain the back-end of the nuclear fuel cycle. Russia's "Proryv" project is developing safe and commercially viable fast reactors that would enable Russia to transition to a two-component nuclear power system in the near to mid-term future. The recently approved Strategy-2018 (Rosatom 2018) document provides insight on the possibility of this transition in some detail. The current study examines the option of completely recycling MA generated after VVER spent fuel reprocessing by adding them to the FR fuel for use in the emerging fast reactor fleet. In this approach, we consider every FR in this system to be as part of commercially viable power plants dedicated to generating electricity for the public. Recycling MA is a complex problem that affects all aspects of the FR nuclear fuel cycle (NFC). The current study focuses primarily on the physical aspects of homogenous MA transmutation in FRs and its implications for the two-component nuclear

energy system. Nevertheless, the authors would like to highlight several technical factors that could play a major part in MA management:

- Am leakage can occur when fabricating U-Pu-MA fuel: a portion of Am will evaporate as the fuel pellet sintering process takes place. Increasing the Am content is expected to increase these leakages;
- Increasing MA content in the fuel significantly adversely impacts fuel radiation properties (substantial increase of fuel dose rates);
- Adding MA leads to increased residual heat generation when operating under short SNF cooling time-frames due to ^{242}Cm accumulation, which complicates SNF management and FR fuel reloading logicstics;
- Adding Cm to the fuel for transmutation is not considered due to increased neutron source intensity and radioactive heat generation (currently storing Cm for 70–100 years until it decays into Pu is the prefered option).

Plutonium and MA balance in VVER and FR fuel

MA recycling efficiency should be determined in relation to the evolving capacity of the nuclear power system, its resource consumption and waste accumulation rates. As a starting point, it is necessary to specify NFC parameters for VVER type reactors operating in an open cycle and FRs operating in a closed cycle. In this study the MA inventory is presumed to consist of only Am and Np. Transmuting Cm in FRs in not considered at the time being. After the relatively short-lived isotopes $^{242\div244}$Cm decay into Pu they can be recycled in standard U-Pu FR fuel. For initial approximation we can assume that MA accumulate in proportion to reactor capacity, therefore many mass characteristics for MA consumption can also be correlated to reactor capacity. In light of this several factors should also be considered:

- MA concentration relative to Pu in VVER spent fuel can reach 20%, but in general the MA concentration in VVER SNF is quite low (~0.1–0.2%);
- Am concentration increases (by a factor of ~4) depending on the SNF cooling time period and can reach from ~3 to ~14% relative to Pu, Np concentrations are stable (in the range of 6% in relation to Pu);
- Prolonged storage of thermal reactor spent fuel complicates MA management;
- The following MA accumulation characteristics (VVER SNF cooling period is 8–10 years) are used as reference values for corresponing calculations: ~15 kg per year for Np and ~ 20 kg per year for Am for 1 GWe installed capacity. This corresponds to 2.1 t MA generated per 1 GWe for the full life cycle of VVER operation;
- The mass balance for MA residing in FR fuel corresponds to 4% concentration in relation to Pu or 0.5% of the entire fuel (of which 0.1% is Np and 0.4% is Am).

The NFC parameters presented in Table 1 can be used to compare MA accumulation in an open and closed fuel cycle. In an open fuel cycle the accumulated Pu, Am and Np can be treated as high-level radioactive waste (HLW). In a closed NFC only 0.1% of the actinides (losses) are encapsulated with fission products as part of HLW. Table 1 illustrates the impact of persuing a closed NFC strategy on waste management characteristics in relation to natural uranium consumption: if the closed NFC option is considered, natural uranium consumption decreases by a factor of 190, MA accumulation in HLW decreases by a factor of 320.

Table 1. Natural uranium consumption and HLW characteristics comparison for open VVER and closed FR nuclear fuel cycles

Parameter	1 GWe VVER		1 GWe FR	
	per year	60 years	per year	60 years
Natural U consumption, t	154	9240	0.8	48
Pu accumulated in HLW, kg	250	14800	1.7	102
Am accumulated in HLW, kg	19	1150	0.073	4.4
Np accumulated in HLW, kg	15	910	0.033	2.0
MA accumulated in HLW, kg	34	2060	0.116	7.0

MA accumulation estimates for the nuclear energy system

According to Strategy-2018 (Rosatom 2018) in 2018 Russia has accumulated 22500 t HM of SNF, of which ~5000 t HM is VVER SNF and 14800 t HM is RBMK SNF. Russia's current Pu stockpile must also be taken into account. As of yet the industry has not started to partition HLW after reprocessing VVER SNF (except cases where Np extraction is necessary). Therefore, we can assume that the MA that were extracted from VVER SNF prior to 2020 will not be recycled in FRs.

The Strategy-2018 document (Fig. 1) considers several scenarios of nuclear power development with two different overall installed capacity growth rates. Alternate variants with different shares of VVER and FR technology are also examined. We can highlight the following key boundary conditions: total nuclear power installed capacity by 2100 reaches 71–92 GWe with FR comprising 31–92 GWe and VVER reactors comprising 40-0 GWe. Table 2 shows aggregated estimates for Pu and MA accumulation for year 2100 (does not include the option of recycling Pu in VVER NFC).

The Pu accumulation parameters in Table 2 take into account FR breeding ratio at a level ~1.05. Adding MA to the fuel at specified concentrations does not affect the breeding ratio. Fast reactor MA are not taken into account

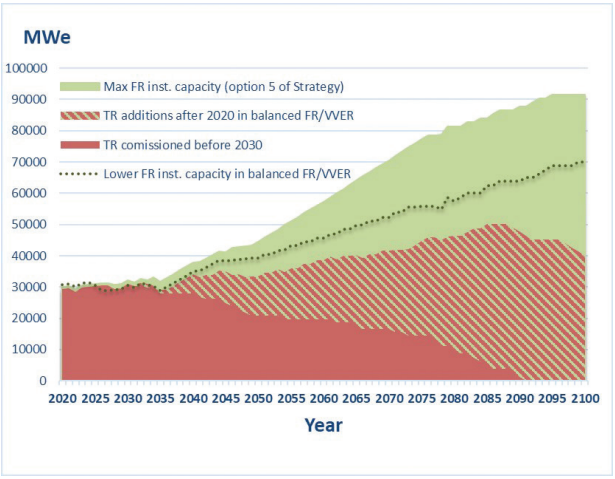

Figure. 1. Russian nuclear power development scenarios in the XXI century.

because they are constantly recycled in FRs. The total amount of Pu accumulated over time determines how many FRs could be commissioned using U-Pu fuel and should be factored in when analyzing MA balances.

Table 2. MA and Pu accumulation estimates (Np and Am) for year 2100 for different nuclear energy system development options

Option	NPP installed capacity	FR / VVER installed capacity	Amount of Pu, t	Amount of Np / Am / MA , t
Max FR inst. capacity (option 5 of Strategy)	92	92 / 0	661	29 / 38 / 67
Balanced FR/VVER capacity (with more FR)	92	52 / 40	1010	52 / 67 / 119
Balanced FR/VVER capacity (with more VVER)	71	31 / 40	988	52 / 67 / 119

By analyzing the results in Table 2 we can summarize the following regarding MA accumulation:

- Maximum MA accumulation rate in VVER SNF is in the range of 1.4–1.7 t/year (VVER installed capacity being 40–50 GWe) and 0.76–0.96 t/year for Am;
- The total amount of MA (Np and Am) accumulated by 2100 varies from 67 to 120 t HM, and 38 to 67 t HM for Am.

According to the 5th variant (with high NPP installed capacity) of nuclear power development per Strategy-2018 after thermal reactor SNF reprocessing the extracted Pu is recycled in a gradually emerging fleet of FRs. It is highly likely that the total inventory of Pu obtained this way will not be enough to commission 92 GWe FR capacity: estimates show that it is possible to commission only 71 GWe of BN-1200 type reactors or 86 GWe of BR-1200 type reactors using available Pu resources specified in Strategy-2018. Taking into account the fact that Pu from VVER SNF is in limited supply, the system could bring into play other sources of fissile material for manufacturing the startup fuel - natural uranium or Pu from RBMK SNF. If all conditions are met, cumulative natural uranium consumption in the XXI century will reach 226 000 t, which is approximately half of Russian's available natural uranium resource base estimated in Strategy-2018 (Rosatom 2018).

Prolonging VVER operation will lead to increased Pu and MA accumulation, and a lower FR share will in turn lead to lower consumption of Pu and MA. This could result in 550–750 excess tones of Pu that could have been otherwise used in FRs. It should be noted that recycling MA without recycling Pu is undesirable, since this option would not allow the nuclear energy system to reach the radiation equivalency requirement (Adamov et al. 2015) due to Pu itself being highly radiotoxic. Nevertheless 66–120 t HM of MA are used as the reference range for further analysis.

MA and Pu recycling efficiency analysis

The theoretical and experimental possibility of transmuting MA in FRs is demonstrated in (Vlaskin et al. 2014) and is considered to be a scientifically proven fact. Nevetheless, today there is still no practical proof that recycling MA in FRs is a technologically and economically viable option. By analyzing SNF radionuclides we can summarize that Pu and Am are the major contributors to potential biological hazard (Adamov et al. 2015). Recycling one element without the other is almost pointless. The work conducted within the "Proryv" project (Vlaskin et al. 2014) demonstrates that by using FRs the radiation hazard of Am is decreased only after repeated multirecycling. Simultaniously recycling Pu and MA is the more preferred option. Another important aspect is that decreasing MA mass using transmutation as a means of lowering overall radiation hazard is ineffective due to the resulting daughter products originating from MA burning.

Finally in one of the more recent studies (Egorov et al. 2019) it was shown that recycling MA in reasonable amounts (4–5%) does not have a negative effect on FR safety and also minimizes the maximim reactivity margin and therfore lowers the risk of a reactivity-initiated accident.

Bearing all these considerations in mind, the authors of this study propose a strategy for MA management where the Pu and MA extracted from VVER SNF is used for FR start-up fuel and for the initial 2–3 reloads. After this initial stage FR spent nuclear fuel is regenerated and the reactor will enter a state of fuel self-sufficiency. After the reactor starts operating using regenerated materials (starting from the 3rd or 4th refueling interval) additional MA from VVER SNF will not be added to the fuel mixture. This approach guarantees that both MA and Pu obtained after VVER SNF reprocessing will be recycled in the FR. The authors of this study would like to highlight the fact that this approach of recycling Pu obtained from reprocessing VVER SNF should be considered as a base case strategy for developing large-scale nuclear power systems.

Maintaining the same proportion of Pu and MA as there is in SNF VVER will lead to a higher MA content in the FR fuel as higher Pu concentrations are used to manufacture it (see Fig. 2). The aforementioned factors (Am leakage, background radiation, FR SNF decay heat and other factors) might potentially limit the mass fraction of MA in the FR fuel.

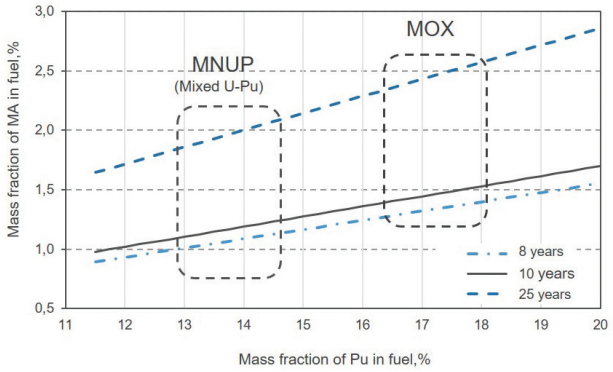

Figure 2. Mass fraction of MA in the FR fuel.

The MA management strategy described above presumes that MA from VVER SNF are multirecycled until they are totally burned and the amount that was burned inside the FR can be used as a criterion for evaluating the efficiency of MA transmutation (see Table 3). The BN-1200 sodium-cooled reactor with mixed nitride U-Pu fuel was used as reference for performing all FR calculations (Babushkin et al. 2020). Table 3 presents key reactor characteristics. The following isotopic composition describes Am extracted from VVER SNF: ^{241}Am/^{242m} Am/^{243}Am – 78.14%/0.13%/21.73%. For Np: ^{237}Np -100%.

Table 3. Recycling Pu and MA from VVER SNF in BN-1200 for the reference option

Parameter	Values for T_{NFC} = 2 years	Values for T_{NFC} = 3 years
Thermal power, MWt	2800	
Electric power, MWe	1200	
Operation cycle length, day	330	
Number of core fuel assemblies	432	
Number of radial blanket assemblies	none	
Core height, cm	83	
Volume ratio of core (Fuel/Structure/Coolant)		
• central fuel assemblies	0.471/0.207/0.298	
• peripheral fuel assemblies	0.497/0.194/0.287	
Pu consumption in start-up load, t	7.34	7.34
Cumulative Pu requirement for first reloads, t	3.30	4.95
Cumulative Pu needed for 1 GWe, t/GWe	8.51	9.83
Pu content in fuel, mass. %	12.6	12.6
Am content in fuel, mass. %	1.07	1.07
Cumulative Am consumption from VVER SNF, t	0.90	1.04
Np content in fuel, mass. %	0.90	0.90
Cumulative Np consumption from VVER SNF, t	0.71	0.82

Figure 3 describes changes in MA concentration in the fuel during multiple recycling in the FR.

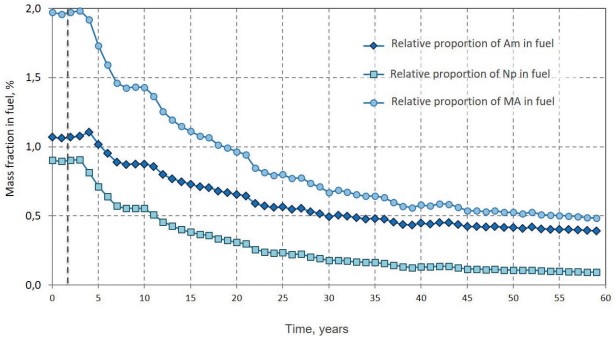

Figure 3. Am concentration variation in fuel with MA.

To summarize one BN-1200 can burn approximately 0.9–1.0 t of Am and и 0.7–0.8 t of Np from VVER SNF, which overall amounts to 1.6–1.8 t of VVER MA. Mass fraction of MA gradually decreases from ~2% to an equilibrium value of 0.5%, which corresponds to the rate of breeding and burning MA in the core. Am concentration decreases from ~1.1% to ~0.4%.

Calculations show that one VVER reactor over its lifetime can generate enough Pu to commission 1.5–1.7 FRs of similar capacity, so 40 GWe of thermal reactor capacity would in turn give rise to 60–68 GWe of FR capacity (assuming that all Pu and MA is effectively recycled in FRs).

"Distributed over reactor lifetime" MA recycling strategy if MA fuel concentration constraints are taken into account

Although simultaneous recycling of MA together with Pu is the desired option, it is not the only one that can be effectively implemented in a two-component nuclear energy system. MA concentration in the aforementioned MA management strategy decreases by a factor of 4 (Figure 3) which means that additional MA can be burned throughout FR operation.

To maximize MA burn rate the authors of this study propose an approach of burning MA from VVER SNF throughout the entire FR fuel life cycle. This would be especially useful in case MA concentration in the fuel was limited due to technological or radiological constraints. In the initial stage of FR operation, the fuel will contain the maximum possible amount of MA. The following approach can then be adopted when the FR switches to regenerated fuel: if technically possible, additional MA from reprocessing VVER SNF are added to the regenerated FR fuel mixture already containing a portion of the MA from initial FR startup loads. This way all following fuel loads in the FR will contain the maximum amount of MA.

In order to perform the necessary calculations Am fuel content was limited to a range of 0.4% to 2%. The RTM-2 (Khomyakov et al. 2020) calculation code was used in order to perform these calculations. Figure 4 shows average annual Am (obtained from reprocessing VVER SNF) consumption as a function of maximum Am content in the BN-1200 fuel.

The total mass of burnable Am was calculated as the difference between loaded and unloaded Am in the fuel summed over all fuel recycling intervals.

It can be summarized that constant addition of MA to the FR closed NFC allows burning 3.5 times more MA compared to the previous approach: 3.6 t of Am or 6.1 t of MA over reactor operating lifetime. It should also be noted that the same amount of Am as in the previous approach can be burned but with much lower concentrations of Am in the fuel - from 1.07% to 0.6% if the FRs under consideration adopt the new approach with constant Am additions.

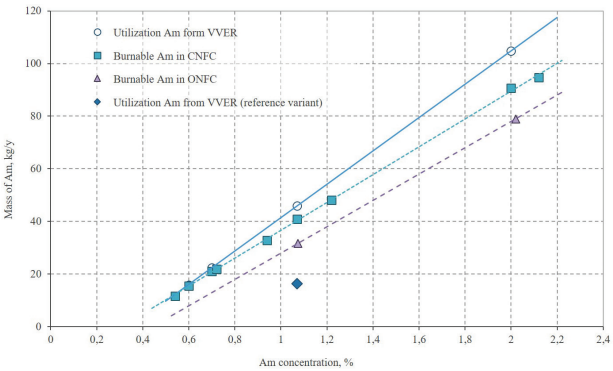

Figure 4. Average annual Am (obtained from reprocessing VVER SNF) consumption depending on maximum Am content in the BN-1200 fuel.

MA utilization in a two-component nuclear energy system

Using the these results we can understand how the MA problem can be resolved pertaining to the Russian two-component nuclear energy development scenarios described earlier in this study. Tables 4 and 5 present the results of different estimates on Am utilization depending on Am concentration in fuel and Np utilization depending on MA concentration for different Russian nuclear power development scenarios.

Based on these results we can make the following conclusions:

- A nuclear energy system reaching 92 GWe of FRs by the end of the century can effectively resolve Russia's MA and Pu accumulation problem by implementing the reference approach where maximum MA concentration in fuel reaches 2%.
- Large scale FR systems where Pu and MA are simultaneously used for fuel fabrication can resolve Russia's MA problem even if MA concentration in FR fuel is limited to 0.5%, although a margin for increasing this concentration would be desirable due to possible future uncertainties;
- Lowering the FR share in the nuclear power fleet and prolonging VVER commissioning well throughout the century with VVER reaching 40 GWe by 2100 will require bringing Am concentration in FR fuel to 0.75% if FR installed capacity by year 2100 reaches 52 GWe and 1.1% if FR installed capacity reaches 31 GWe.

Table 4. Summary on Am utilization in FRs for different Russian nuclear power development scenarios with limits to Am fuel concentration taken into account

TR/ FR capacity for year 2100	Am accumulation from VVER SNF	Am utilization in FRs corresponding to Am concentrations in fuel				Reference variant
		0.6%	0.7%	1.1%	2.0%	1.1%
92 / 0 GWe	38 t	70 t	99 t	203 t	456 t	68 t
52 / 40 GWe	67 t	40 t	56 t	115 t	258 t	39 t
31 / 40 GWe	67 t	24 t	33 t	68 t	154 t	23 t

Table 5. Summary on Np utilization in FRs for different Russian nuclear power development scenarios with limits to MA fuel concentration taken into account

TR/ FR capacity for year 2100	Np accumulation from VVER SNF	Np utilization in FRs corresponding to following MA concentrations in fuel				Reference variant
		1.1%	1.5%	2.0%	3.7%	2.0%
92 / 0 GWe	29 t	71 t	117 t	185 t	400 t	56 t
52 / 40 GWe	52 t	40 t	66 t	105 t	226 t	32 t
31 / 40 GWe	52 t	24 t	39 t	62 t	135 t	19 t

Conclusion

The study focuses on relevant two-component nuclear power development scenarios for Russia in the XXI century. Depending on the scenario there will be approximately 38 to 67 tonnes of Am, or 67 to 120 tonnes of MA (Am+Np) that will require some kind waste management solution.

The authors propose two approaches to recycling MA from reprocessed VVER SNF:

- MA are recycled together with Pu, which is in turn used for strarting up FRs, and are later recycled onwards with the FR's own MA until they are completely burned;
- MA are added to the FR fuel throughout FR operating lifetime (60 years or more) so that MA or Am concentration does not exceed a set maximum value.

The first relatively simple approach allows guaranteed recycling of MA and Pu arising from VVER SNF reprocessing and fundamentally solves the issue of VVER SNF and MA accumulation. Pu is used exclusively to build up a large-scale fleet of FRs. This approach eliminates the accumulated MA by means of manufacturing FR fuel with ~2% MA concentration which will allow one BN-1200 to burn 1.66 t MA, which corresponds to burning 15 kg/year of Am and 13 kg/year of Np.

Similar results regarding MA utilization can be achieved with lower concentration of MA in the FR fuel by distributing them throughout FR operating lifetime (60 years) and maintaining a constant level of their concentration in the fuel. Calculation results demonstrate that a 0.6% concentration for Am and 0.5% concentration of Np in the FR fuel would be sufficient. Achieving higher concentrations of Am in the fuel is desirable for commercial interests with

the aim of burning extra MA arising from possible foreign SNF reprocessing. The amount of extra Am burned this way can range from 22 kg/year to 115 kg/year.

From an energy system point of view, the solution to the MA problem is defined by the scale of the FR fleet. If 92 GWe of FRs are commissioned then the Am problem can be resolved without using any dedicated actinide burner reactors. If the amount of Am concentration in FR fuel is limited by technological constraints to 0.75% h.a. this would allow for recycling Am from the entire inventory of reprocessed VVER SNF even if FR installed capacity reaches 52 GWe and VVER capacity 40 GWe by 2100. Finally, if Am concentration is increased to 1.1% h.a. the Am accumulation problem can be resolved even if FR capacity is limited to 31 GWe by 2100.

We can therefore conclude that delaying FR deployment will surely have a negative impact on the capability of the nuclear power system as a whole to deal with the MA problem and will require developing fuel compositions with much higher properties in terms of radiation hazard control (due to higher concentrations of MA). These circumstances must be taken into account with regard to the work being conducted on nuclear power development scenarios within the framework of the Russian nuclear energy strategy.

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