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Research Article

Some economic aspects of reducing americium production in a two-component system of thermal and fast reactors*

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Abstract

The article analyzes the economic aspects of reducing the production of americium during the transition from a single-component nuclear energy system (NES) based on thermal reactors in an open fuel cycle to a two-component system with thermal and fast reactors in a closed nuclear fuel cycle. Scenarios for the development of these systems in Russia up to the end of the century are modeled. Two methods are considered for reducing the production of americium in a two-component NES with fast sodium reactors. The first method, closing the fuel cycle for plutonium in BN reactors of SFR type, is based on the use of plutonium separated from spent nuclear fuel of thermal reactors with the shortest possible (according to technical specifications) time for MOX fuel preparation and use thus preventing the main part of plutonium-241 from decay into americium. The second way is transmutation of americium. The study was carried out by using the mathematical code CYCLE designed for modeling of the NES with closed nuclear fuel cycle (NFC). The technical and economic data used in the paper was taken from published studies of Russian specialists and materials of European Union specialists presented in the IAEA/INPRO SYNERGIES project. The results of the research show that the efficiency of closing the NFC by using plutonium from thermal reactors in MOX fuel of fast sodium reactors is comparable to the efficiency of the homogeneous transmutation considered in the paper. The combination of the americium accumulation prevention method and transmutation method might significantly reduce the rate of the americium accumulation in a nuclear energy system, but the estimated costs of the considered homogeneous transmutation can significantly worsen the economic performance of sodium fast reactors.

Keywords

minor actinides, thermal reactors, fast reactors, closed nuclear fuel cycle, MOX fuel, transmutation economics

Introduction

Minor actinides (actinoids) are transuranic elements, except plutonium. In nuclear power, minor actinides (MA) include neptunium (Np), americium (Am) and curium (Cm). The minor actinide issue has become topical in connection with the search for a more appropriate way for the actinide handling than deep geological disposal in

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an open NFC. Development of an alternative to the MA deep geological disposal option is explained to a great extent by the fact that the integrity of artificial and natural barriers cannot be guaranteed for dozens and hundreds of years and there is a risk of high-level toxic radionuclides release into the biosphere.

A major step towards reducing the radioactive nuclear waste (RW) radiotoxicity and heat generation was the development of a technology for extracting plutonium, neptunium and uranium from SNF (PUREX process). This technology, which allows using the energy potential of plutonium as fuel for large-scale nuclear power has not been yet used extensively in conditions of the low NPP construction pace worldwide and the low cost of available natural uranium, but it has served as a guide in searching for a safer way for the final RW disposal than disposal of high-level SNF. Its logical evolution has been the development of the SNF partitioning and transmutation concept involving separation and further use or elimination (transmutation) of all environmentally hazardous radionuclides. After plutonium is separated from SNF, the key contributors to the RW radiotoxicity and heat generation are minor actinides (Bergelson et al. 2005; IAEA-TECDOC-1587 2018). Transmutation is proposed as the key MA handling technique (Salvatores et al. 1994). This is expected to minimize the impact of artificial radionuclides on the biosphere (Adamov et al. 1999). The latter is the purpose of the RW final safe disposal in the Strategy for the Development of Nuclear Energy in Russia in the First Half of 21st Century, 2001. Achieving this goal will take a lot of time and efforts but the progress in this field meets in full the fundamental RW handling principle ALARP, that is, reducing the radiation hazard to such low level as reasonably practicable with regard for social and economic factors.

A large number of papers have been devoted to the issues of the MA radiochemical separation and transmutation, which explore largely physical and technological transmutation issues. This paper compares two approaches to resolving the problem of MA accumulation in the sodium fast reactors (SFR): 1) involvement of freshly separated plutonium from VVER SNF with a high content of Pu-241 in the SFR fuel, which makes it possible to reduce the rate of the americium-241 accumulation in the nuclear energy system; and 2) transmutation of americium in the reactor core. In both cases economic aspects of the americium accumulation reduction are discussed as the most complex issue in terms of the MA handling. The results obtained by the authors are compared with the data provided by the European Union experts in a report under the IAEA/INPRO SYNERGIES Project (Nuclear Energy Series No. NF-T-4.9 2018).

Pathways for the minor actinide formation and handling

A large number of MA isotopes are formed in nuclear reactions and in the process of radioactive nuclei decay in nuclear fuel. Many of these are long-lived alpha-active isotopes which are highly hazardous when entering human body (Kutkov et al. 2008) and the most destructive ones in terms of damaging any matrix that incorporates radioactive waste (Divide the Indivisible 2003). The MA isotopes, which are produced in reactors and have major effect on fuel and waste management, are Np-237, Am-241, Am-242m, Am-243, Cm-242, and Cm-244. Np-237 that is generated on the U-235 isotope, has a comparatively low activity and does not play a major part in the HLW heat generation and radiation field formation.

The formation chains for the most important americium and curium isotopes are presented in Fig. 1 (Decay schemes of radionuclides. Energy and intensity of radiation. Part 2, book 2 1987; Gusev and Dmitriev 1998;

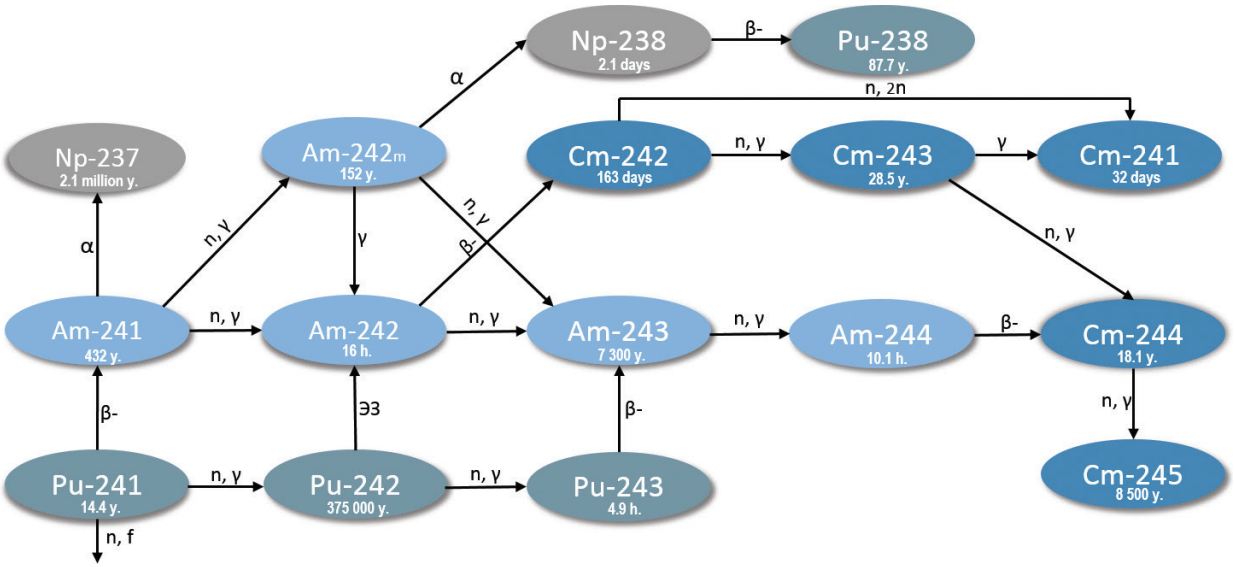

Figure 1. Minor actinide formation chains.

Korobeynikov et al. 2014). In nuclear reactor SNF, the predominant americium isotope is Am-241. Practically all Am-241 is produced in the reactor and in SNF through the Pu-241 beta decay. The half-life of Pu-241 is 14 years, and that of americium-241 is 432 years. In the process of the SNF storage without reprocessing, the quantity of Am-241 in it increases through the Pu-241 decay, and the SNF alpha activity grows as the result.

Due to the absorption of the neutron by the Am-241 isotope, metastable Am-242m is generated in the thermal reactor fuel, which transforms into Np-238 as the result of alpha decay with $T_{1/2}$ = 152 years. The beta decay of Np-238 is accompanied by a major yield of high-energy gamma radiation (0.6 to 1.0 MeV) which has major effect on the dose rate from irradiated fresh fuel with americium. The Am-241, Am-242m and Am-242 americium isotopes are highly heat emissive. Due to this, under consideration is the addition of only 1% to 3% of americium to the BN-1200 reactor fresh fuel. of The spent fuel assembly (SFA) heat generation and radiotoxicity, the cooling times being up to about two hundred years, will be defined by fission products (FD), though minor actinides will contribute as well to the SFA radiation characteristics. After two hundred years of SNF cooling and up to about five thousand years, minor actinides make most of the contribution to the SNF heat generation and activity.

The heat generation and radiation characteristics of MA elements define the selection of the individual technique for handling with each of them by way of combining the main approaches to the RW management: reduced generation, beneficial use, elimination (transmutation), storage. Similar MA handling approaches that take into account specific physicochemical characteristics of different MA has been developed for SFR in the Russian Federation (Divide the Indivisible 2003; At Atomexpo about the raw material supply of the nuclear fuel cycle 2023) and in France (Report on sustainable radioactive waste management 2012).

The MA recycling studies show that neptunium can be used as fast reactor fuel since it is easily extracted together with uranium in the course of SNF reprocessing, does not worsen further the radiation situation, and does not create major difficulties due to heat generation. It is not practicable to have curium involved in the fuel cycle in the foreseeable future since it will lead to a major growth in the fuel heat generation and the resultant neutron and gamma radiation. A more appropriate way is to store it. Most of the curium contained in SNF is the Cm-244 isotope which has a half-life of only 18 years. It is therefore practicable to store curium for about 100 years. In the course of this period, nearly 80% of curium transforms into plutonium which can be used as part of nuclear fuel.

In terms of the handling, the most troublesome radionuclide is Am-241. This radionuclide ($T_{1/2}$ = 432 years) creates major difficulties in SNF and RW handling due to high heat generation and a high radiation dose rate. This paper considers two ways of americium accumulation decreasing in a nuclear energy system: reduction of the Am-241 production by preventing its formation from Pu-241 (Dekusar et al. 2019; Gulevich et al. 2020; Larionov et al. 2020) and transmutation.

The feasibility of transmutation in a sodium fast reactor is acknowledged by experts and was demonstrated in France in the process of irradiating in the reactor core several fuel pellets with a homogeneous addition of americium (Report on sustainable radioactive waste management 2012). The transition from several pellets to the transmutation scale needed for the nuclear energy system requires primarily that the compliance with nuclear and radiation safety requirements is justified. Nuclear safety regulations and design limits for the FA heat generation and personnel exposure doses limit the permissible content of americium in fuel. Both conditions are met when the content of americium in the BN-1200 reactor core fuel is not more than 3%.

Transmutation of americium will also require the necessary adaptation and upgrading of the NFC control, monitoring and biological shielding systems, with new challenges to arise in this respect. Radiochemical reprocessing of fuel will require MAs to be extracted from SNF on a commercial scale and separated further into fractions. At the present, this technology is at the development stage, both in Russia and abroad. The feasibility of the technology was demonstrated in laboratory conditions, but its commercial deployment will require extra R&D.

Powder metallurgy processes, similar to those used for MOX fuel fabrication (powder preparation, fuel pellet, fuel element, FA fabrication), can be used to fabricate fuel with MAs. With the americium content in powders being up to 3%, the heat generation and neutron radiation intensity will be twice as high as without americium, and the equivalent dose rate will be nearly an order of magnitude higher. The presence of americium will require an increased protection against neutron and gamma radiation, as well as extra measures for temperature monitoring in the fuel fabrication process. The studies undertaken show that fabrication of fuel with americium accounts for most of the contribution to the extra costs involved in the fuel cycle when implementing the homogeneous americium transmutation option.

The growth in the heat generation and neutron and gamma radiation intensity in fresh fuel and the growth in the SNF heat generation will also lead to complicated transport operations, in particular, to more container shipments.

Therefore, the americium transmutation option for sodium fast reactors requires updating some of the reactor systems and NFC infrastructure, as well as changing their operating modes and the number of container shipments. All this will lead to the high costs of implementing the americium transmutation option. Presented below are preliminary results from estimating these costs for the BN-1200 reactor design (Alekseev et al. 2016; Tuzov et al. 2022), which are compared with similar estimates obtained for the European SFR-1440 reactor (Nuclear Energy Series No. NF-T-4.9 2018).

Estimation of the americium transmutation cost

As compared with data in Nuclear Energy Series No. NF-T-4.9 2018, Table 1 presents obtained estimates for the increase in the electricity generation cost due to extra costs of upgrading the reactor and the fuel cycle facilities for the homogeneous transmutation of americium in BN-type reactors with its content in fuel being ~ 3% (Alekseev et al. 2016; Tuzov et al. 2022).

Table 1. Contribution of reactor and fuel components to electricity cost, %

Option	BN-type reactor			SFR-type reactor		
	Full	Reactor	FC	Full	Reactor	FC
MOX fuel without Am	100	88	12	100	91	9
MOX fuel with Am	110	89	21	106	92	14

The data in the table allow concluding that the extra costs involved in transmutation of americium in sodium fast reactors affect the electricity cost fuel component (CFC) more than the reactor component. The share of the costs for upgrading the BN reactor facility and for the SFR was ~ 1%, while the share of the extra costs for americium transmutation in the BN and SNF fuel cycle was 9% and 5% respectively. A higher relative share of the costs for transmutation of americium in the BN fuel cycle is explained by the fact that the unit cost of the electricity generation in an SFR (in US dollars per kW·h presented in Nuclear Energy Series No. NF-T-4.9 2018 is higher than for BN reactors (Alekseev et al. 2016). As a result, approximately equal extra costs for americium transmutation in the fuel cycle lead to a higher value of relative costs in a BN-type reactor.

The data presented in Table 1 and the technical and economic data for BN reactors (Alekseev et al. 2016; Tuzov et al. 2022) and the SFRs (Nuclear Energy Series No. NF-T-4.9 2018) make it possible to obtain preliminary estimates for the unit cost of americium transmutation. For the BN-1200 reactor, the cost of homogeneous transmutation in the reactor core in the 2023 US dollars was estimated to be ~ 0.5 mln$/kgAm. No transmutation cost estimate is presented for the SFR-1440 reactor in Nuclear Energy Series No. NF-T-4.9 2018 but it is easily calculated from the data contained therein and amounts to a value close to the BN estimate.

The study shows that there are three major causes for the high cost of americium transmutation in the option considered in the paper:

- small quantity of americium addition to MOX fuel permitted by the limits defined by the design and the nuclear and radiation safety requirements – the limits that can be mitigated as part of the design modification but will require an increased cost of the design;
- low efficiency of transmutation with which less than a quarter of the americium added to the fuel burns up (this is an unavoidable physical constraint typical for americium transmutation in a fast neutron spectrum caused by the americium content being slightly in excess of the so-called equilibrium value);
- higher cost of fuel fabrication with americium than fabrication of pure MOX fuel – a technological constraint.

The progress on these issues would make it possible to reduce the americium transmutation cost.

Minor actinide accumulation scenarios

The MA accumulation in Russian nuclear power during this century was calculated at JSC IPPE (Dekusar et al. 2019) based on the scenario studies conducted using the CYCLE code (Kalashnikov et al. 2016; Dekusar et al. 2022). The code is designed for mathematical simulation of the nuclear fuel cycle with reactors of different types taking into account the isotopic composition of nuclear materials at all cycle stages.

The basis for building the scenarios was the roadmap for commissioning/decommissioning Rosenergoatom's power units, forecasts for the evolution of nuclear power up to the end of this century, and the results of other studies undertaken as part of the computational and analytical justification for the Russian nuclear power evolution strategy options.

Two scenario options have been considered for the evolution of nuclear power. It was suggested in the first (reference) scenario, which represents the evolutionary path for the evolution of Russian NES, that the nuclear power structure would consist by the end of the century predominantly of one component, that is, of thermal reactors operating in an open NFC. Two-component nuclear power consisting of thermal and fast reactors with a shared closed NFC was considered in the second scenario. The pre-processing SNF cooling time is five years for VVERs with uranium fuel, seven years for VVERs with MOX fuel, and four years for BN-type reactors. The involvement of plutonium from VVER SNF with a short cooling time (freshly isolated plutonium) in the fuel cycle of sodium fast reactors makes it possible to reduce the accumulation of americium as compared with the one-component system option.

The structure of the NES installed capacities up to 2100 for the two scenarios is presented in Fig. 2 (Dekusar et al. 2019).

In the evolutionary scenario with a one-component NES, SNF from all VVER-400 and BN-600 reactors is processed throughout their design life with regenerated nuclear materials stored in warehouses. It assumes that the BN-600 reactor operates on uranium throughout the operating time, and the BN-800 reactor starts and operates on uranium until 2022 and operates further, up to the end of the service life, on MOX fuel.

The second scenario suggests that (apart from the BN-600 and the BN-800) large BN-1200 fast reactors based

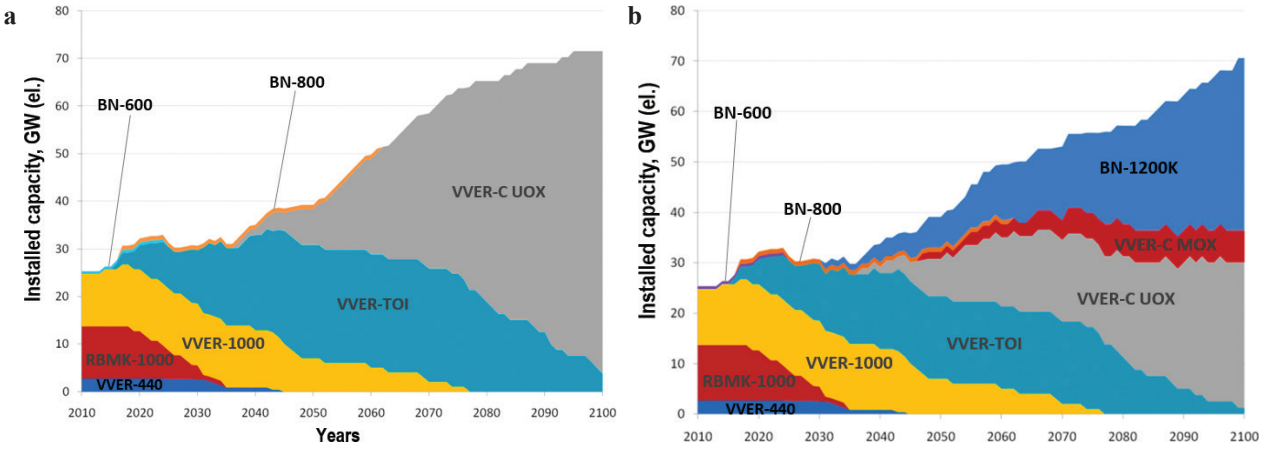

Figure 2. Structure of the Russian NES installed capacities in evolutionary scenarios for a one-component system (**a**) and a two-component system (**b**).

on MOX fuel begin to be put into operation in 2030, and advanced VVER-S thermal reactors start to be commissioned in 2037, some of these being converted to MOX fuel. Until 2050, energy-grade plutonium from thermal reactor SNF is used for the MOX fuel fabrication. BN SNF reprocessing and use of BN plutonium starts in 2050 (Tuzov et al. 2020). Table 2 shows full the neptunium and americium accumulation in the systems under consideration.

Table 2. Accumulation of americium in two scenarios for the development of Russian NP, t

MA	Scenario (a) with VVER				Scenario (b) with VVER+BN			
	2020	2035	2070	2100	2020	2035	2070	2100
^{237}Np	8.1	13.4	33.3	56.1	8.1	12.3	22.7	33.1
^{241}Am	15.0	30.0	71.7	117.8	15.0	27.8	50.3	72.3
^{243}Am	1.6	2.6	6.9	12.6	1.6	2.4	7.0	16.6
Total Am	16.6	32.6	78.6	130.4	16.5	30.248	57.3	88.9

Table 3 presents accumulation of americium for the one- and two-component structure of Russian NP since 2020. By 2020, 16.6 tons of americium were accumulated in Russia, but this quantity was omitted in the table to illustrate the comparison of the americium accumulation rate for the two NES structures. In two-component structure plutonium from VVER SNF starts to be used in fast reactor fuel in 2022.

As it follows from the table, the plutonium closed NFC in sodium fast reactors leads to a major slowdown in the americium accumulation in the NES which is greater than the americium transmutation in the homogeneous option. This is explained by the accelerated involvement of plutonium-241 (the potential source for Am-241) in the fast reactor fuel cycle. Due to the fact that this isotope is of the highest value with respect to the fission process, then even its once-trough passage through the BN-1200 reactor core allows reducing practically by 40% the accumulation of americium in the system while not handling americium proper. The effect of a plutonium closed fuel cycle is especially marked at the initial stage of the fast reactor deployment as part of the NES when the initial fast reactor fuel load will require much plutonium from thermal reactor SNF and, accordingly, much plutonium-241.

Table 3. Americium-related figures for Russian NP evolution scenarios

Characteristics	Years			
	2020	2035	2070	2100
	Scenario 1: one-component NES			
Accumulation of Am-241, t	0	15.0	56.7	102.8
	Scenario 2: two-component NES			
Accumulation of Am-241 with Pu closed NFC / reduction against Scenario 1, t	0	12.8 / 2.2	35.3 / 21.4	57.3 / 45.5
Reduction of Am-241 accumulation via transmutation, t	0	0.3	11.2	39.7
Accumulation of Am-241 with closing and transmutation / reduction against Scenario 1, t	0	12.5 / 2.5	24.1 / 32.6	24.5 / 78.3
Homogeneous transmutation costs, bln$	0	0.2	5.6	20.0
Electric power growth potential for BN reactors on Pu-241 saved from decay in Am-241, GW	0	0.75	6.7	13.0

A plutonium closed fuel cycle with the design-permitted short-term cooling of thermal reactor SNF prior to the MOX fuel fabrication and fabrication time does not require extra costs. At the same time, homogeneous transmutation with addition of up to 3% of americium to fuel is expected to complicate considerably the fuel handling process and worsen greatly the economic performance of sodium fast reactors which is shown by the economic estimates given in Table 3. The efficiency of preventing americium production in the event of a closed NFC can be increased via reducing even more the time from the thermal reactor SNF unloading to the loading of MOX fuel made of it into fast reactors (e.g., for up to 5 years), but this possibility requires to be comprehensively justified both technically and economically. The data in Table 3 show that preventing the decay of plutonium-241 into americium-241 will lead to the valuable isotope retained in regenerated fuel the fission of which will allow using more efficiently the potential of uranium-plutonium fuel for the growth of the sodium fast reactor capacities.

Conclusions

The results of the computational studies show that the efficiency of reducing the americium accumulation with a plutonium closed NFC in sodium fast reactors has a value comparable with the homogeneous transmutation option considered in the paper. A plutonium closed fuel cycle with the shortest technologically possible thermal reactor SNF cooling and MOX fuel fabrication time, as the design permits, does not require extra costs, is being implemented already today, and will be especially effective at the fast reactor commissioning stages when much plutonium will be needed for the fast reactor initial loads. With closing in regenerated fuel, plutonium-241 is saved as a valuable isotope, the fission of which will allow obtaining extra energy. Therefore, the NFC closing in sodium fast reactors via using freshly separated plutonium from thermal neutron reactors with a short cooling time, is an efficient way to reduce the accumulation of americium in a two-component system of thermal and fast reactors which comply with the key waste handling principle, that is, prevention of waste formation.

However, single closing for freshly isolated plutonium in BN reactors is not enough to avoid in full the accumulation of americium in the scenario of the Russian two-component NES evolution by the end of the century. The combination of plutonium closing and transmutation could reduce substantially the americium production in the NES and possibly avoid its accumulation within the system, but the estimated costs of transmutation in the considered homogeneous option are expected to worsen greatly the fast reactor economic performance or require substantial time expenditures.

A potential option for improving the situation may be using a more economically acceptable combined homogenous and heterogeneous ways for americium transmutation or even using specialized burner reactors, confirming the feasibility of which and, moreover, demonstrating its economic efficiency will require a long time.

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