Research Article

Minor actinides transmutation in equilibrium cores of next generation FRs

Alexander V. Egorov[1], Yurii S. Khomyakov[1], Valerii I. Rachkov[1], Elena A. Rodina[1], Igor R. Suslov[1]

1 *Innovative and Technology Center by "Proryv" Project, 2/8 Krasnoselskaya M., Moscow, Russian Federation*

Corresponding author: *Elena A. Rodina* (rea@proryv2020.ru)

Abstract

The Russian Federation is developing a number of technologies within the «Proryv» project for closing the nuclear fuel cycle utilizing mixed (U-Pu-MA) nitride fuel. Key objectives of the project include improving fast reactor nuclear safety by minimizing reactivity changes during fuel operating period and improving radiological and environmental fuel cycle safety through Pu multi-recycling and MA transmutation.

This advanced technology is expected to allow operating the reactor in an equilibrium cycle with a breeding ratio equaling approximately 1 with stable reactivity and fuel isotopic composition. Nevertheless, to reach this state the reactor must still operate in an initial transient state for a lengthy period (over 10 years) of time, which requires implementing special measures concerning reactivity control.

The results obtained from calculations show the possibility of achieving a synergetic effect from combining two objectives. Using MA reprocessed from thermal reactor spent fuel in initial fuel loads in FR ensures a minimal reactivity margin during the entire fast reactor fuel operating period, comparable to the levels achieved in equilibrium state with any kind of relevant Pu isotopic composition. This should be combined with using reactivity compensators in the first fuel micro-campaigns.

In the paper presented are the results of simulation of the overall life cycle of a 1200 MWe fast reactor, reaching equilibrium fuel composition, and respective changes in spent fuel nuclide and isotopic composition. It is shown that MA from thermal and fast reactors spent fuel can be completely utilized in the new generation FRs without using special actinide burners.

Keywords

Fast reactor, nitride fuel, spent nuclear fuel, minor actinides, reactivity margin, equilibrium cycle

1. Introduction

In the Russian Federation, technology complex concerning closure of the fuel cycle based on the use of mixed fuel (U-Pu-MA) is under development within the framework of "Proryv" project. The key goals of the new technology are to improve fast reactor nuclear safety by minimizing maximum excess reactivity value and increase radiation and en-

vironmental safety of the fuel cycle by means of multiple recycling of Pu and transmutation of minor actinides (MA).

Core BR ≈ 1 value, as well as core equilibrium mode characterized by stable values of reactivity and isotopic composition of the fuel can be achieved in the new generation reactors using high density fuel, in particular, nitride fuel (Rachkov et al. 2015, Adamov et al. 2015a, Adamov et al. 2015b, Adamov et al. 2015c). Also, it is well known that transmutation of MA as fuel component has favorable effect on reactivity behavior during the core lifetime (Kooyman et al. 2018).

The results presented in this paper are of analytical studies showing the possibility of synergy effect as a result of combination of the two goals, i.e. implementation of core equilibrium mode and utilization of MA from spent nuclear fuel (SNF) of both fast and thermal reactors. Power fast reactors of the new generation are considered. In addition to cost effective energy production these reactors are capable of minimizing radwaste amount thus making unnecessary involvement of purpose-designed burner reactors into the nuclear power system.

A significant problem is related to the transient period of operation of the reactor initially loaded with the fuel containing either non-equilibrium composition plutonium extracted from thermal reactor's SNF or low active plutonium with low fraction of even isotopes. In the course of multiple fuel recycles both reactivity and fuel composition would significantly change before equilibrium state is reached.

Studies required carrying out special procedure of simulation of the long life cycle of the reactor core (up to 30 - 60 years) and development of relevant tool (computer code) and technique.

2. Problem statement and reactor core life cycle simulation technique

It was already shown at the stage of preliminary study that during transient period of the reactor operation special measures would be required for controlling excess reactivity over the core lifetime depending on isotopic composition of the initial fuel loading. Physically it is related to successive changes of isotopic composition of the basic components of Pu and U fuel in the course of their recycling. In order to compensate for these changes and maintain core critical we have adopted a technique of correction of plutonium mass fraction maintaining reactor critical at the beginning of each reactor run.

However reactivity behavior with the fuel burn-up depends on isotopic composition of Pu even though fuel multiplication factor maintenance by the above method is taken into account. An additional tool is required to control reactivity behavior. We consider adding MA to the fuel in various proportions to be such a tool.

There also should be noted another physical process influencing reactivity behavior. In the initial core loading there are no fission products, so it has high excess reactivi-

ty which should be compensated by means of introduction of fixed absorber-based reactivity compensators (FRC) replacing the row of the fuel subassemblies. This approach was used at the early stage of operation of the Russian fast reactors BN-600 and BN-800. However fuel breeding ratio of the initial core loading is also high, and it also has an effect on reactivity curve in the course of fuel burn-up. In this paper presented are the results of an effort to use FRC in the optimal way for controlling core BR at the early stage of reactor operation in closed nuclear fuel cycle.

The main problems concerning analytical studies included not only the need to equalize fuel composition in the course of reactor refueling over the transient operation period before equilibrium reactor mode is reached, but also simulation of refueling system taking into account installation and replacement of fixed absorber-based reactivity compensators at the early operation stage. Sodium cooled large size reactor with mixed uranium-plutonium nitride fuel (Vasiliev et al. 2017, Adamov el al. 2017) was chosen for detailed simulation of its full life cycle. The model of the reactor is presented in Fig. 1.

The core of sodium cooled fast reactor of 2800 MW thermal power consists of 432 hexagonal fuel subassemblies (SA) and 31 control rods.

Studies were performed on the evenly-fractional core refueling pattern used when entering steady state operation mode and during steady state operation period. This pattern implies equal number of subassemblies handled during each refueling cycle and equal refueling intervals. The main characteristics of the core refueling pattern are given in Table 1.

In Table 1 presented is the average number of the core subassemblies replaced during one refueling cycle. Taking into account actual SA refueling groups (see Fig. 2) depending on operation interval, the number of replaced SA is 96–101.
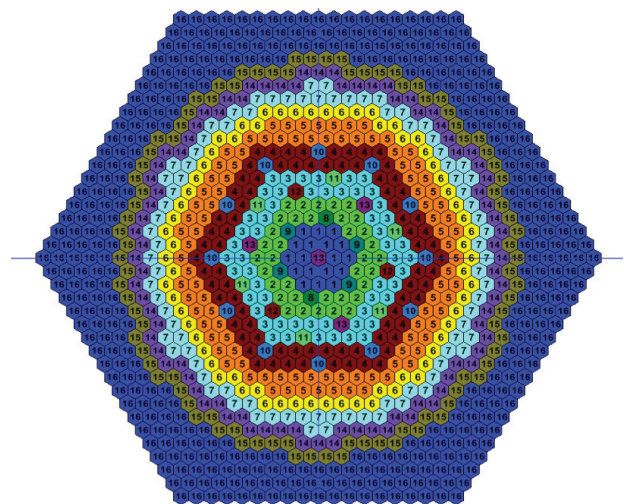
Figure 1. Fast reactor core diagram: 1–7 – fuel subassemblies; 8 – control rod; 9–10 – shim rods; 11 – safety rod; 12 – passive safety rod (actuated on coolant temperature change); 13 – passive safety rod (actuated on temperature change); 14 – 15 – boron shielding; 16 – steel shielding subassemblies (first version).

Table 1. Main characteristics of the core model.

Thermal power, MW	2800
Number of subassemblies	432
Reactor run duration, eff. days	330
Number of cycles	4/5/6
Reactor shut-off for refueling, eff. days	30
Duration of external fuel cycle, years	2
Number of takeoff runs, in which "native" fuel is not used	3
Design lifetime, years	60
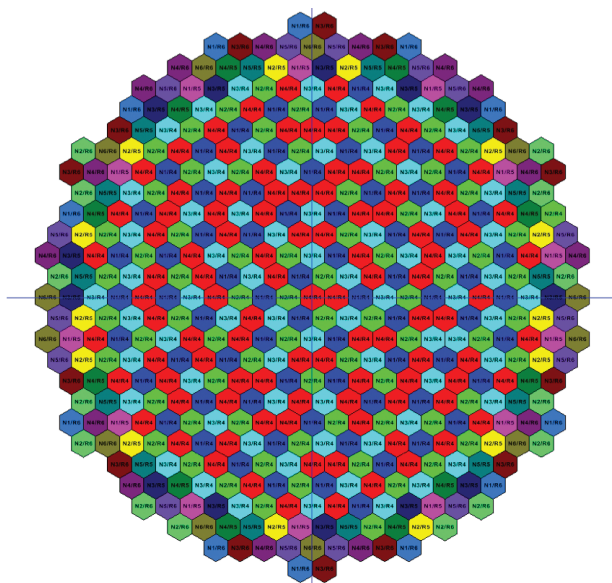
Figure 2. Evenly-fractional core refueling pattern: N – refueling cycle number; R – refueling frequency.

3. Description of fuel scenarios under consideration

Wide range of plutonium isotopic compositions has been considered as applied to the initial core loading (Table 2):

- MNUP fuel based on stockpile low active plutonium with addition of waste uranium (0.1% U-235);
- MNUP fuel fabricated on the basis of plutonium having near-equilibrium reactor-grade isotope composition (long-term storage of thermal reactor's SNF before its reprocessing);
- MNUP fuel on the basis of stockpile reactor-grade plutonium from VVER with high Pu-241 content after the short-term storage.

It will be shown hereafter, that Pu-241 content is a critical factor influencing reactivity behavior with the fuel burn-up (the closer to equilibrium content about 3–4 %, the better). Maximum Pu-241 content 9.3 % was adopted, while its minimum content was about 1 % (option 2). MA involvement into the nuclear fuel is effective not only from the standpoint of their transmutation but also with regard to excess reactivity minimization. That is why studies were carried out on all options of fuel isotopic compositions with added MA. The logic is simple: if SNF

Table 2. Isotopic compositions of transuraniums (Pu and MA) in the fuel taken for calculations.

Isotopes	Option 1	Option 2	Option 3	Option 4
Pu-238	0.015	0.0013	0.0240	0.012
Pu-239	0.614	0.9172	0.6130	0.683
Pu-240	0.247	0.0655	0.2180	0.232
Pu-241	0.0715	0.0117	0.0930	0.028
Pu-242	0.049	0.0043	0.0520	0.042
Np-237	–	–	–	–
Am-241	0.0035	–	–	0.003
Am-242m	–	–	–	–
Am-243	–	–	–	–
Cm-244	–	–	–	–
Cm-245	–	–	–	–
Total	1.000	1.000	1.000	1.000

from thermal reactor is used as plutonium source for fast reactor start-up, then after its reprocessing it is desirable to use not only plutonium, but also all other actinides in the proportion they are present in SNF.

In thermal reactor's SNF max fraction of each Np and Am actinide is about 8.5% relative to plutonium amount, in the whole making 17 %, i.e. up to 2.2 % of the total mass of heavy atoms in fast reactor fuel. Depending on the time of spent fuel storage, Pu-241 and Am-241 fractions will vary, their sum being constant. MA fraction in SNF of VVER reactor can be as high as 25 % relative to Pu. As regards fast reactor fuel having Pu mass fraction (enrichment) about 13–14 %, MA fraction in it can reach 3 % value.

As it has been mentioned above, initial fuel loadings are characterized by high core BR value, this resulting sometimes in the increase of reactivity with the fuel burn-up and in high value of max excess reactivity. Physically it is caused by the fact that in the initial fuel loading there is no neutron absorption by fission products and, hence, in the fresh fuel core neutron balance is better than that in the end of the core lifetime. In order to get over the difficulty it is proposed for the initial operation stage to replace some fraction of the fuel with absorbing material, which would act as a fixed (in contrast to the movable shim rods) reactivity compensator and simulate neutron absorption by fission products.

4. Results of analysis of fuel composition effect on reactivity balance

Results of comparative estimates of reactivity behavior with the fuel burn-up for various compositions of loaded fuel are presented in Fig. 3. It should be noted that reactivity behavior in transient period strongly depends on isotopic composition of initial Pu. Max value of excess reactivity for the fuel burn-up varies from ~0.4 % Δk/k to ~0.8 % Δk/k with equilibrium value of ~0.2 % Δk/k or even less.

Correlation between excess reactivity and Pu-241 fraction can be seen for reactor-grade plutonium reactor-grade isotope composition: the higher initial Pu-241 fraction, the
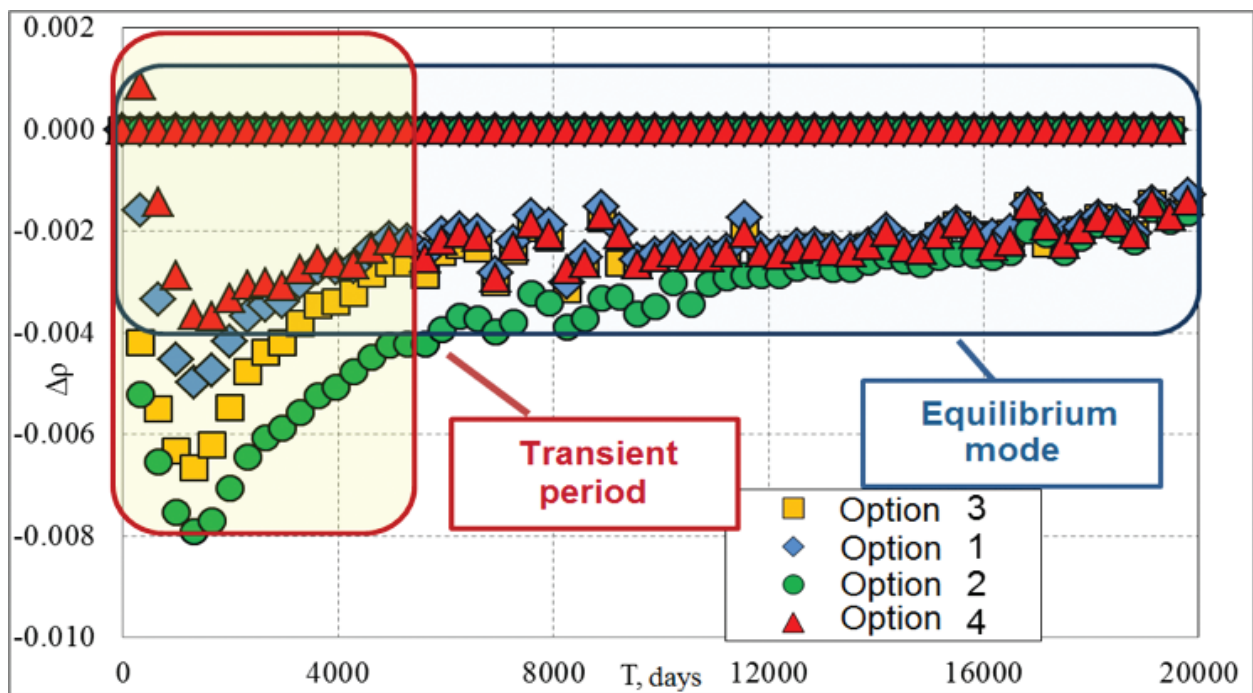
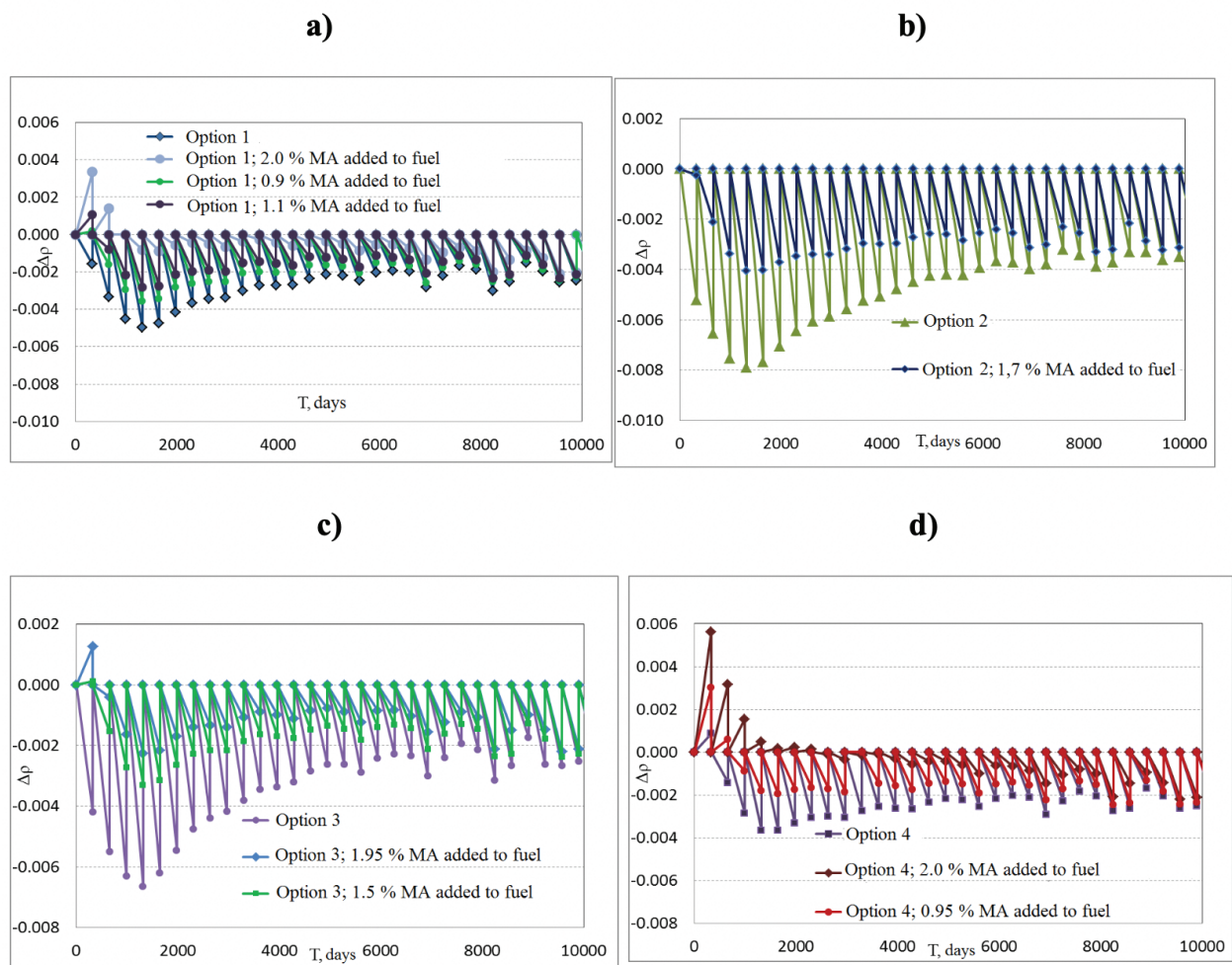**Figure 3.** Reactivity behavior for the initial options.

Figure 4. Reactivity behavior in the core with minor actinides added to the initial fuel loading.

more durable and more troublesome transient period. However, in case of low active plutonium having large fraction of the other fissionable isotope Pu-239, as well, stabilization of reactivity curve at the equilibrium level takes maximum time, and maximum value of ~0.8 % Δk/k is reached. It should be noted that in these options there were no MA in the initial fuel loading, but then their gradual accumulation and recycling took place (except for Cm isotopes).

Results of simulation of transient period with Np and Am from thermal reactor's SNF added to the initial fuel loading are presented in Fig. 4. Amount of MA in the fuel varied. It can be seen from the results, that within the framework of adopted approach with realistic MA concentrations reactivity change becomes more favorable, i.e. both reactivity overshoot (reactivity change during the reactor run) and transient period duration decrease.

So, minor actinides act as certain specific "burnable poison", and their fraction in the fuel can be used as an additional parameter for excess reactivity optimization (Fig. 4).

However the problem arises in the initial reactor runs. It can be seen in Fig. 4 that excess reactivity for the initial fuel loading is present in all options but option 2. It is this fact that is caused by excessive fuel production at the early core operation period. Fixed absorber-based reactivity compensators (FRC) were installed in the initial core loading for the purpose of compensation of excess reactivity. Time of FRC presence in the core was optimized according to the goal. The results are presented in Fig. 5.

It can be stated that simulation has shown the possibility to correct the initial state of reactivity behavior by fitting it within the range of equilibrium state.

5. Results of calculation of isotopic composition of recycled fuel

Fig. 6 shows of variation of fuel nuclide compositions as relative deviations of mass fractions of plutonium and minor actinides (Np, Am) from equilibrium values over the whole life cycle for various initial compositions. By equilibrium isotopic composition we mean plutonium isotopic composition for the reference option at a point in time – 60 years.

Results of calculations presented above have shown that reactivity is being stabilized relatively rapidly, characteristic time corresponding to the fuel lifetime. Plutonium composition comes to equilibrium during rather long time period: about 20 years for reactor-grade plutonium and 50–60 years in case of using low active Pu. Stabilization of MA isotopic composition takes rather long time: about 30–60 years, equilibrium concentration being equal approximately to 0.4 wt. %. This means that MA from VVER's SNF are completely burnt, and there is a balance between produced and burnt MA of fast reactor, i.e. the rate of MA production is equal to that of their incineration. This can be interpreted as the mode of complete incineration of "native" MA.
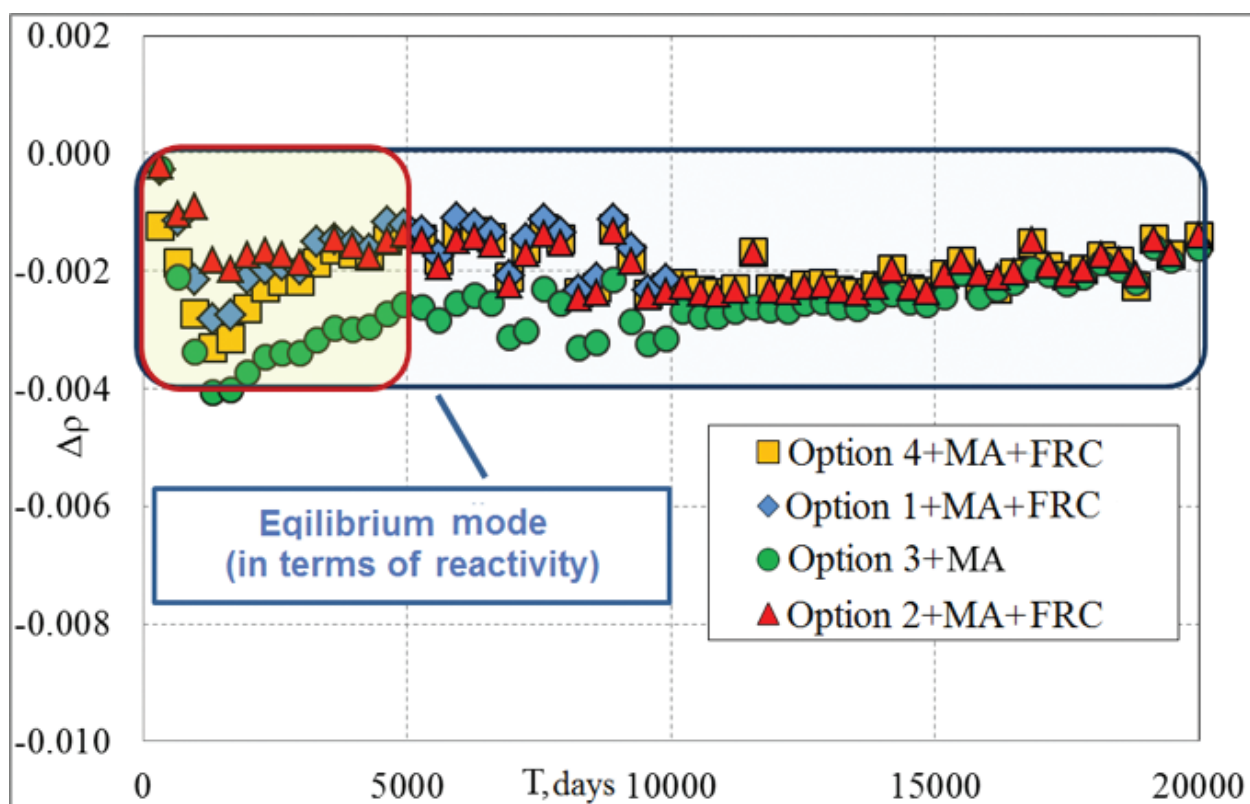

Figure 5. Reactivity behavior in the core with minor actinides added to the fuel and installed FRC.

a) Pu-239

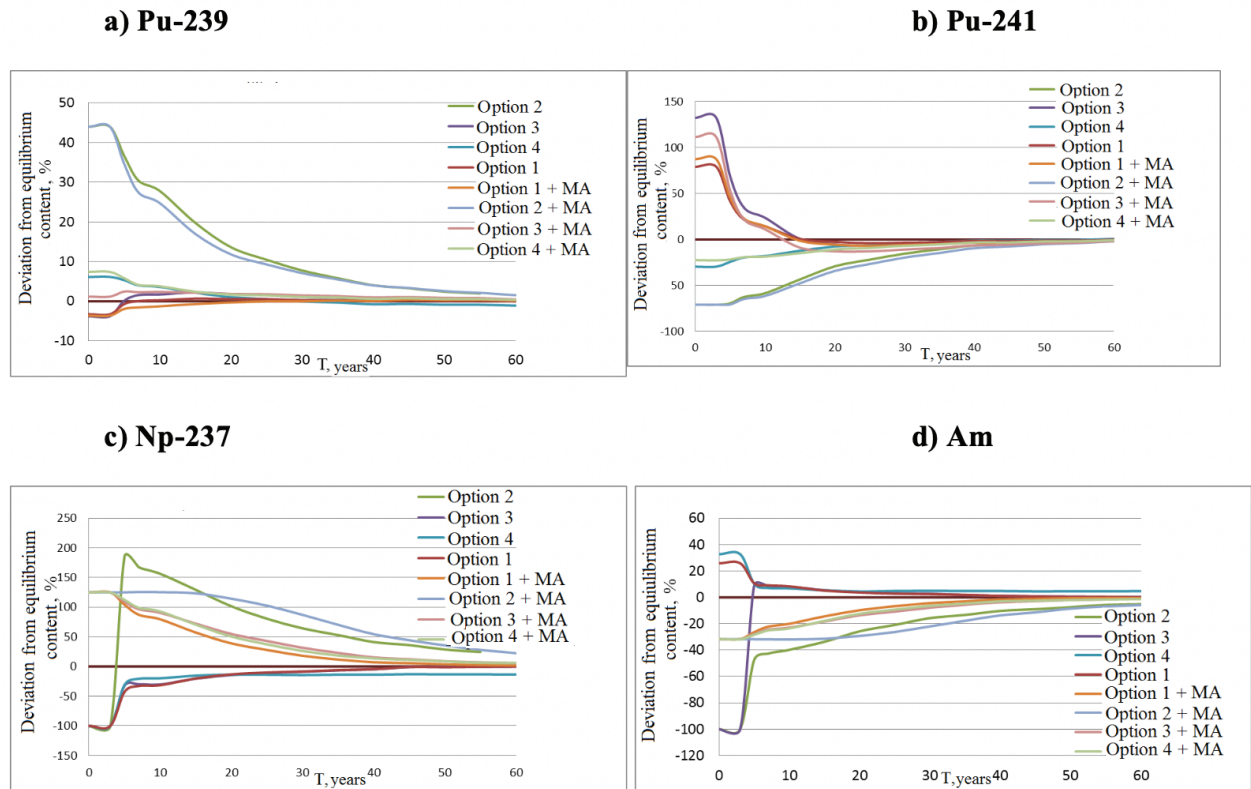**b) Pu-241**

c) Np-237

d) Am

Figure 6. Relative deviation of Pu and MA content from equilibrium value for various initial loadings during life cycle.
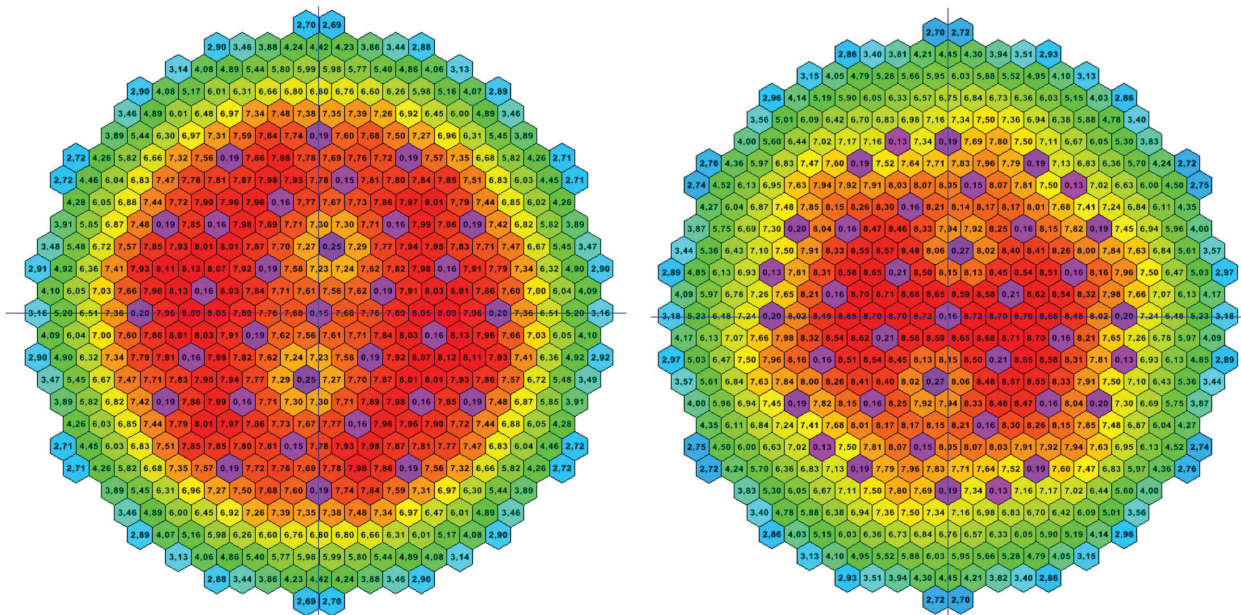

Figure 7. Power distribution over the core without FRC (left) and with 6 FRC, MW.

Maintaining proper value of excess reactivity for several initial irradiation cycles is most critical from the standpoint of nuclear safety. Besides, reactivity equilibrium is reached much earlier than the entire asymptotic equilibrium state characterized by similarity of compositions of loaded and unloaded fuel, its multiplying characteristics and stable reactivity of the whole reactor core.

6. Results of analysis of SA neutron flux and power patterns

SA replacement with fixed reactivity compensators causes change of SA power and, hence, fuel element linear power. As an example, there presented are the results of

calculation of radial power profile of the reactor core for option 1 of fuel composition without FRC and with 6 FRC installed in the core at the beginning of interval (Fig. 7).

After 6 FRCs were installed, max power of SA in the bulk increased from 8.13 up to 8.72 MW, and for SA in the last but one row the increase was from 6.05 up to 6.13 MW. Max linear power of central core subzone SA increased from 448 up to 485 W/cm, and for SA in the last but one row the change was insignificant, namely: from 477 up to 463 W/cm. So, replacement of 6 fuel subassemblies with FRC resulted in 8 % increase of max linear power of the fuel elements.

7. Conclusion

Set of studies has shown the possibility of organic combination of solving MA transmutation problem with assurance of high level of nuclear safety inherent to fast neutron reactors with equilibrium core. In contrast to the other factors, MA application has a positive impact on max excess reactivity value, and MA mass fraction parameter can be used for optimization of the transient mode preceding equilibrium mode of closed nuclear fuel cycle.

Calculations show the possibility of the core operation with equilibrium reactivity maintained over the whole life cycle of the reactor. It is proposed to specify and separate concepts of "equilibrium core", i.e. the core in which reactivity change does not exceed K_{eff} value with the fuel burn-up during the core lifetime, and "equilibrium fuel" which is formed in the course of multiple recycling of reprocessed fuel irradiated in the equilibrium core with BR~1.

Hereby, U and Pu multiple recycling and MA transmutation in power fast reactors facilitate solving the problem of utilization of radwaste from thermal reactors SNF reprocessing with subsequent complete incineration of produced Np and Am in fast reactor fuel without introduction of purpose-designed burner reactors into the nuclear power system.

References

- Adamov EO, Orlov VV, Rachkov VI, et al. (2015a) Nuclear power with inherent safety: exchange of obsolete paradigm, and criteria. Proceedings of the Russian Academy of Sciences. Power Engineering 1: 13–29. https://doi.org/10.1134/S0040601515130029
- Adamov EO, Zaboud'ko LM, Matveev VI, et al. (2015b) Comparative analysis of advantages and drawbacks related to the use of metal and mixed uranium-plutonium nitride fuel in fast reactors. Proceedings of the Russian Academy of Sciences. Power Engineering 2: 3–15.
- Adamov EO, Lopatkin AV, Rachkov VI, et al. (2015c) Radiation-equivalent circulation of radioactive nuclides in nuclear fuel cycle – effective alternative to the deferred solution of the problem of accumulation of spent nuclear fuel. Proceedings of the Russian Academy of Sciences. Power Engineering 6: 15–25.
- Adamov EO, Rachkov VI (2017) New technological platform for the national nuclear energy strategy development. Thermal Engineering 64(13): 945–951. https://doi.org/10.1134/S004060151713002X
- Kooyman T, Buiron L, Rimpault G (2018) A comparison of curium, neptunium and americium transmutation feasibility. Annals of Nuclear Energy 112: 748–758. https://doi.org/10.1016/j.anucene.2017.09.041
- Rachkov VI, Adamov EO, Lopatkin AV, Pershukov VA, Troyanov VM (2015) Fast reactor development programme in the Russian Federation (FR 13). INTERNATIONAL ATOMIC ENERGY AGENCY, Fast Reactors and Related Fuel Cycles: Safe technologies and sustainable scenarios, March 4–7, 2013, Paris, 93–102.
- Vasiliev BA, et al. (2017) Development of the new generation power unit with the BN-1200 reactor. (FR 17). INTERNATIONAL ATOMIC ENERGY AGENCY, Fast Reactors and Related Fuel Cycles, June 26–29, 2017, Yekaterinburg, Russian Federation (IAEA-CN-245-402).