Features of the Nuclear Fuel Cycle Systems Based on Joint Operation of Fast and Thermal Reactors

V.Dekusar, A.Moseev, A.Kalashnikov, P.Moseev

State Scientific Centre of the Russian Federation – Institute for Physics and Power Engineering (IPPE), Obninsk, Russia

E-mail: amoseev@ippe.ru

Abstract. The analysis was made of a model scenario to transfer the two-component nuclear power system (NPS) that consists of thermal reactors of the VVER-TOI type and high power fast reactors of the BN type to the equilibrium mode with full spent nuclear fuel reprocessing and complete recycling of separated plutonium. The specific logistics was developed to use plutonium of various isotopic compositions in the system of fast and thermal reactors. The results of computational fuel cycle simulation are presented for the two-component NPS considered.

Key Words: Simulation, Nuclear fuel cycle, Plutonium composition.

1. Introduction

A significant amount of plutonium has been accumulated and is still being accumulated in the spent fuel of various reactors for the period during which the nuclear energy exists.

The isotopic vector of plutonium produced in reactors varies considerably depending on the type of reactor, fuel burnup and the time elapsed from the moment of its unloading as part of spent nuclear fuel (SNF) from the reactor where it was produced to its loading as a fuel component to another reactor.

For the two-component nuclear power system based on thermal and fast reactors it is fundamental to have plutonium exchange between these types of reactors within a joint closed nuclear fuel cycle (NFC). The composition of plutonium going to fast and thermal reactors can vary within a wide range because it will not only depend on the reactor features, but also on the NFC management.

2. Use of Plutonium of Various Quality in Thermal and Fast Reactors

Plutonium isotopes differ significantly in terms of their nuclear and physical properties. Thus, physical characteristics (safety parameters included) of the reactor where plutonium is used as a fuel will depend on its isotopic composition. The same isotopes have different importance in different types of reactors that use plutonium:

- Even plutonium isotopes in the reactor with fast neutron spectrum (FR) as well as odd isotopes make positive contribution to the cycle duration;

- In the VVER type reactor with thermal neutron spectrum even isotopes are neutron absorbers and they make negative contribution to the cycle duration.

There is a notion of plutonium equivalent, i.e. a unit mass of a certain plutonium isotope is assumed equal to such an amount of ^{239}Pu that impacts the functional under consideration (in this case it is a reactor cycle duration) in the same way as the unit mass of the considered isotope (*see FIG.1.).*

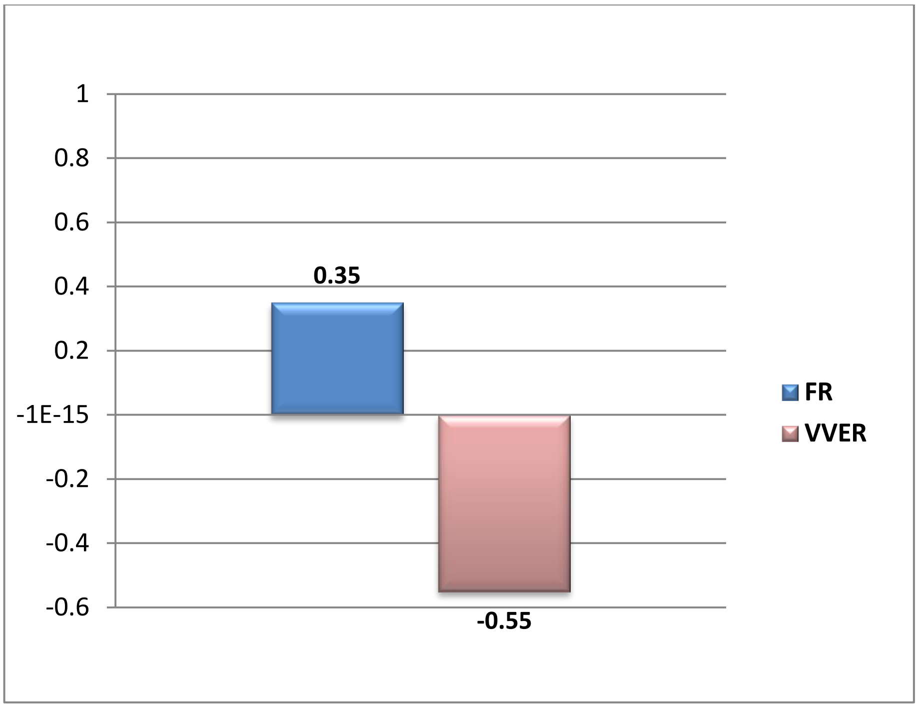

FIG.1. ^{240}***Pu*** *plutonium equivalents for reactors with different neutron spectra.*

By the plutonium quality (plutonium equivalent) is meant the ^{239}Pu mass that corresponds to the unit mass of plutonium of the given composition in terms of its effect on the reactor cycle duration.

If plutonium is used from different sources and is characterized by a different isotopic composition, the reactor parameters can be maintained at the same level by varying plutonium content in the fuel. In this case, the plutonium weight content in the fuel turns out inversely proportional to its quality.

3. Fast Reactor Transition to Equilibrium Mode

Let us consider the simplest case of fuel cycle (FC) closure (*see FIG.2.*), with the use of plutonium separated from the SNF of different types of reactors only to arrange initial loadings and partial loadings of a fast neutron reactor, and then with switching over to the loading of the reactor with own plutonium and gradually getting to steady-state operation conditions when the composition of loaded and unloaded plutonium has been stabilized (equilibrium mode).

All the considered scenarios were simulated with the use of the CYCLE code [1].

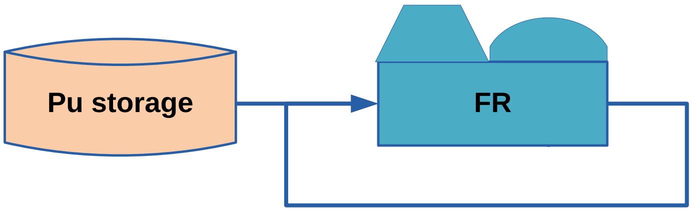

FIG. 2. An example of the simplest NFC layout

In case of this type of fuel cycle layout:

- with an increase in the number of recycles, the Pu content in the fuel does not depend on the initial isotopic composition and asymptotically tends to the same value;
- the contents of isotopes in loaded and unloaded plutonium also tend to asymptotic (equilibrium) distribution distinguished by a low amount of ^{238}Pu, ^{241}Pu и ^{242}Pu;
- asymptotic contents of Pu in the fuel and its asymptotic isotopic composition are determined by the characteristics of the given reactor and the fuel cooling time. If the initial Pu composition differs significantly from the asymptotic one, the time required to finally get this asymptotic contents turns out rather long and actually equal to the reactor design lifetime;
- due to low contents of ^{241}Pu and significant amount of ^{240}Pu, the reactor burnup reactivity margin under the asymptotic conditions is close to the minimum one as compared to all the other considered options of reactor operation with Pu of different compositions. The Pu vectors are shown in Figure 3. Own plutonium - "FR";
- to speed up the process of reaching the equilibrium mode, it is recommended to use the stored plutonium with the composition closest to the asymptotic one with the aim to prepare the initial loading and partial loadings at the first stage of reactor operation.

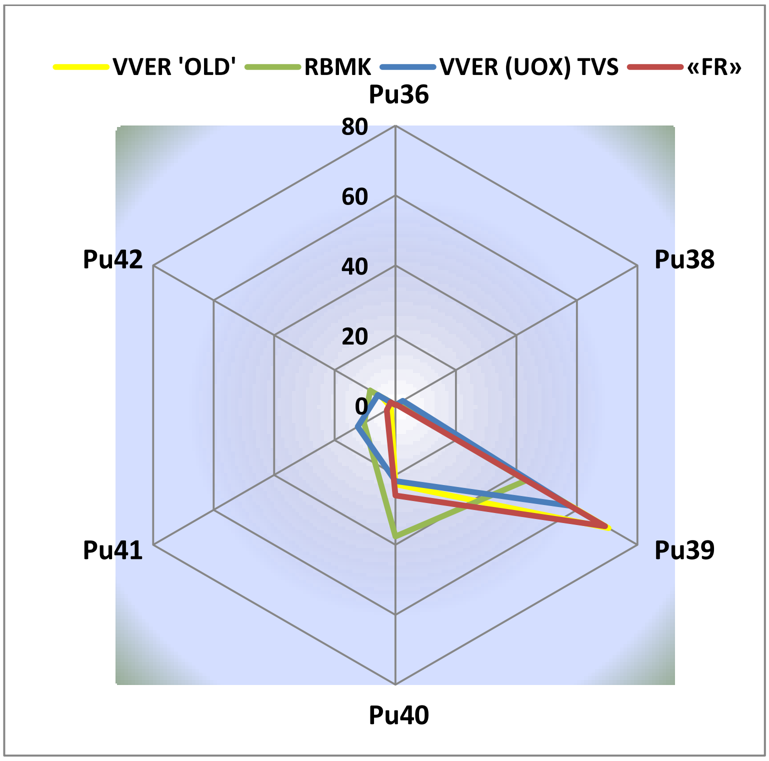

FIG.3. Plutonium vectors at the simplest NFC layout.

4. Stabilization of Nuclear Energy Scenarios

Let us consider the model scenarios for the development of nuclear energy, when after reaching a certain power level of the system the annual electricity production will be stabilized:

- one-component nuclear power based on natural uranium - VVER (UOX) in open nuclear fuel cycle (ONFC) - reference; (Scenario 1);
- two-component nuclear power - VVER (UOX)+FR with the priority of FR SNF reprocessing (Scenario 2);
- two-component nuclear power - VVER (UOX) + FR with the priority of VVER SNF reprocessing (Scenario 3);
- two-component nuclear power - VVER (UOX + MOX) + FR (Scenario 4).

A special feature of the plutonium-balanced system regarding Scenario 4 is that SNF of both reactor types is reprocessed completely, and all separated plutonium is used for MOX – fuel fabrication. At the same time MOX-fuel is used not only in FR reactors, but also as a partial load in VVER reactors. A similar equilibrium scenario was considered in [2].

The goal of simulation is characterization of fuel cycles of stationary nuclear power system based on VVER reactors and high power FR reactors with oxide fuel of different composition. The characteristics of reactor systems with partial or complete reprocessing of spent nuclear fuel and plutonium recycling are compared with the characteristics of the reference system that only consists of uranium-fuelled VVER reactors operating in an open fuel cycle.

Consideration is given to the following aspects as the system characteristics:

- share of reactors (FR and VVER with uranium fuel, and with a partial load of MOX fuel);
- share of MOX fuel assemblies (FAs) in VVER reactors;
- natural uranium consumption;
- plutonium content in MOX - FAs of VVER and FR reactors;
- SNF and plutonium accumulation;
- plutonium vectors obtained.

In addition to SNF reduction, the fast reactors perform a function of improving the quality of plutonium in closed nuclear fuel cycle (CNFC) (plutonium is used for deployment of new reactors and is burnt in VVER MOX-FAs).

Figures 4-6 show the installed capacity of operating reactors in the stabilization scenarios based on:

- 19 VVERs (Scenario1),
- 7 VVERs replaced with FR reactors (Scenarios 2-3),
- remaining VVERs gradually transferred to partial MOX-fuel loading (Scenario 4)

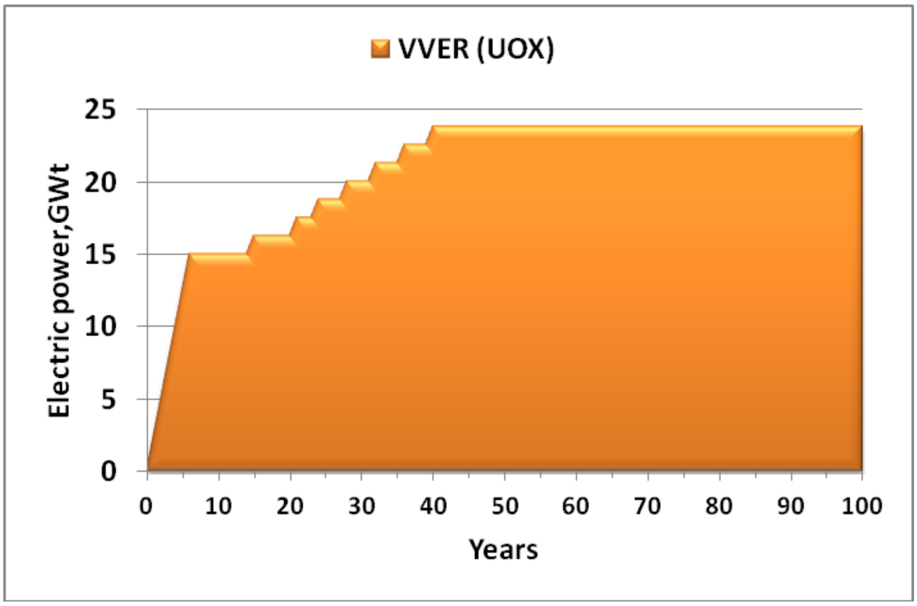

FIG. 4. Reference Scenario 1 – open NFC (VVER (UOX)).

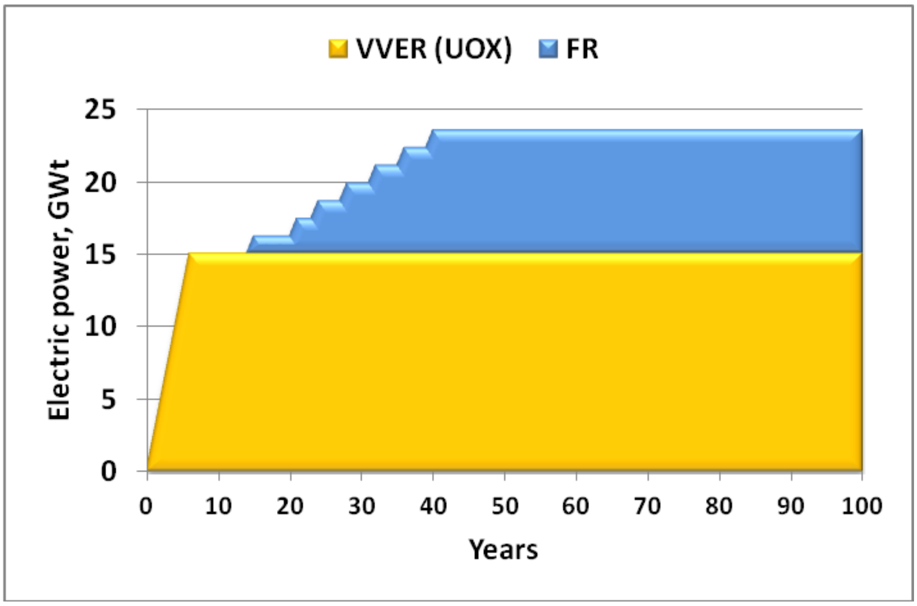

FIG. 5. Scenario 2-3 – closed NFC (VVER (UOX) + FR).

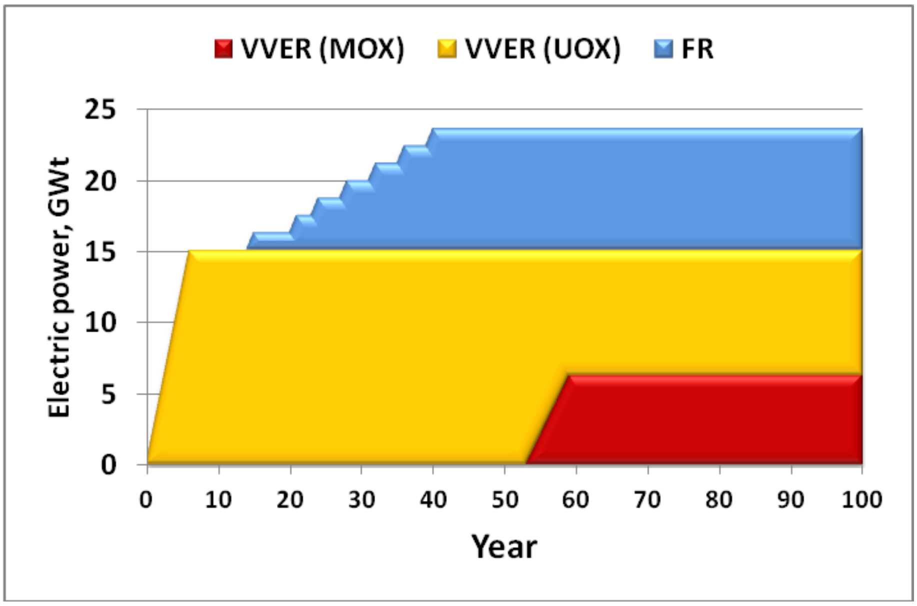

FIG. 6. Scenario 4 – VVER (UOX + MOX) + FR.

5. Stages of transition to stabilization in Scenario 4

The diagrams of the first NFC stage are shown in Figures 7 and 8.

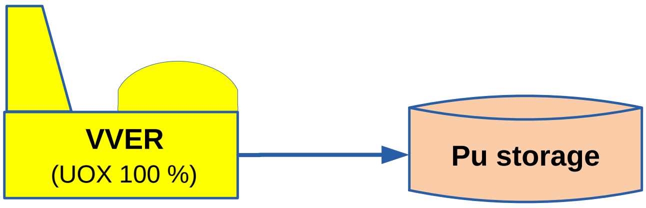

FIG. 7. Diagram "A": NFC with VVER SNF reprocessing and plutonium accumulation.

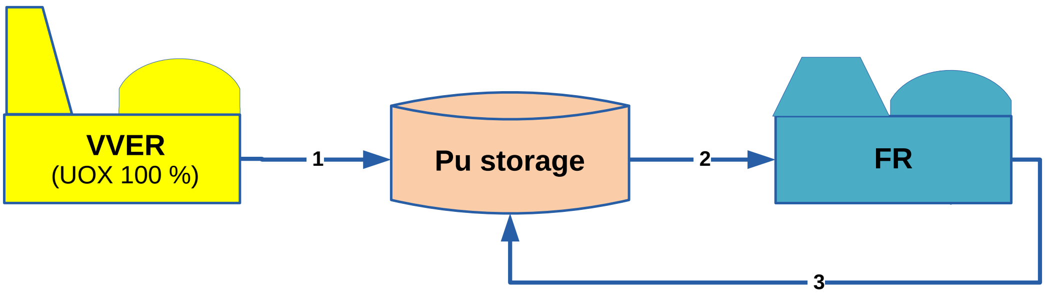

FIG. 8. Diagram "B": two-component NFC with VVER and FR SNF reprocessing and FR reactor deployment on the basis of plutonium balance.

At this stage the thermal and fast reactor SNF is completely reprocessed without any accumulation.

The diagram of the second NFC stage with the steady-state conditions reached is given in Figure 9.

For recycling of the accumulated plutonium and transition of the system into the equilibrium mode, the VVER reactors are transferred to partial MOX-fuel load. SNF of thermal and fast reactors is completely reprocessed, without any accumulation.

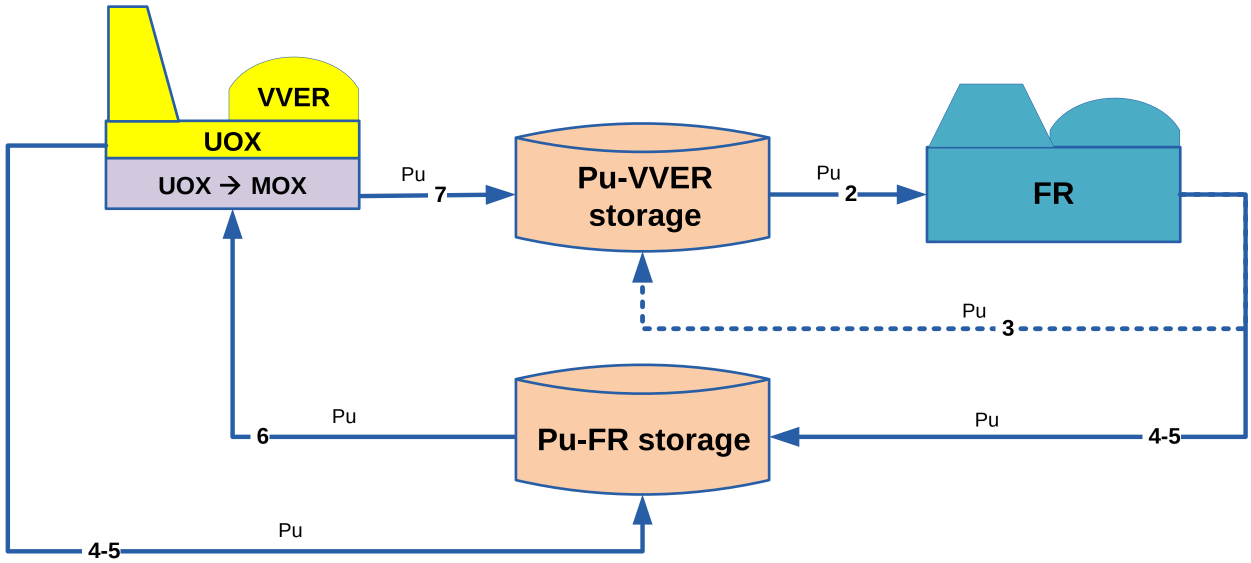

FIG. 9. NFC diagram with transition into the steady-state condition.

As the steady-state condition is approached, specific accumulation of plutonium tends to zero. Figure 10 shows SNF accumulation for the scenarios under consideration.

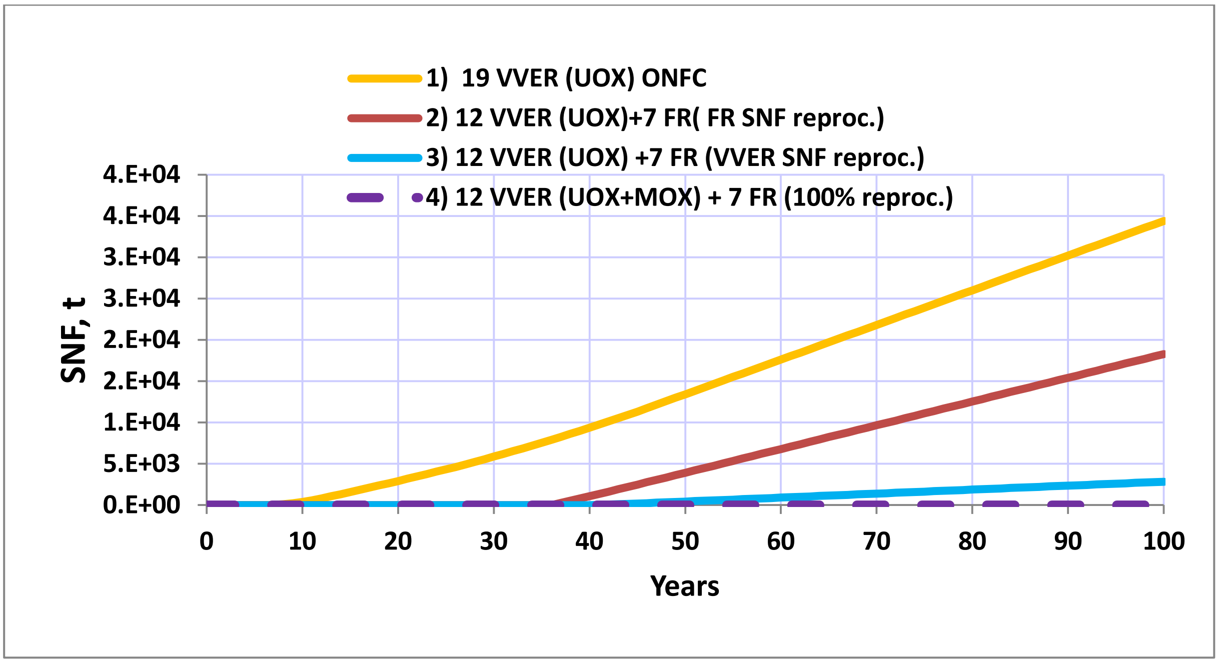

FIG. 10. SNF accumulation in storage facilities.

Figure 11 illustrates the annual uranium consumption in the reference and innovation scenarios.

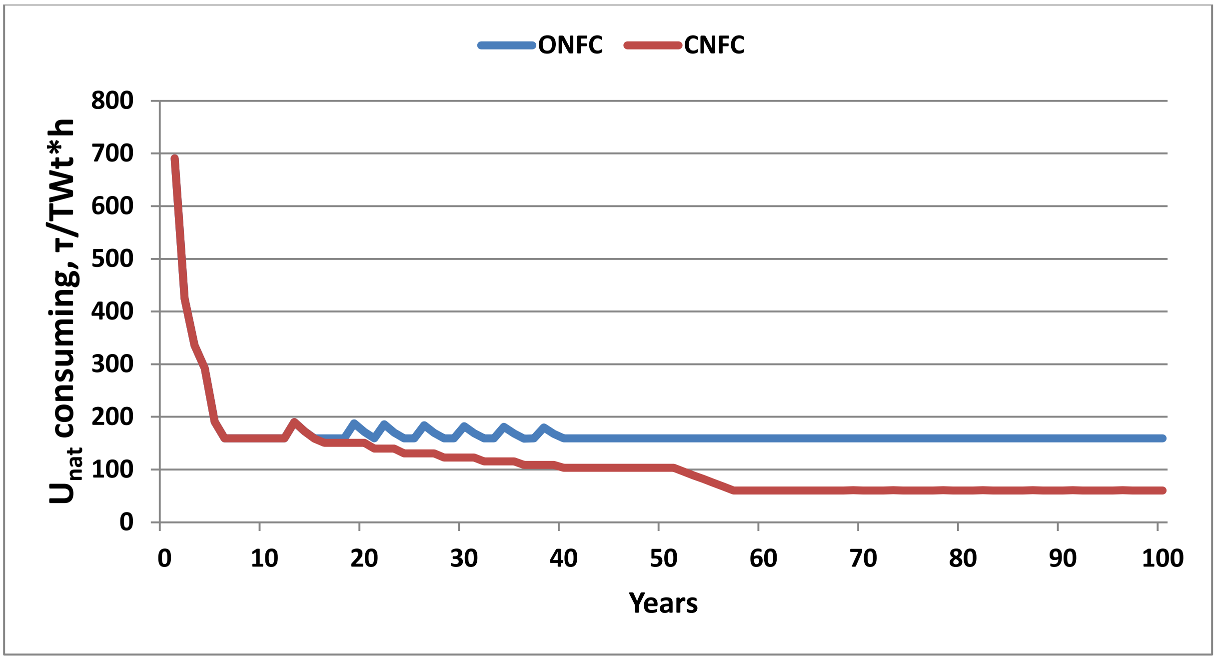

FIG. 11. Dynamics of annual natural uranium consumption for open and stationary fuel cycles.

Plutonium store balance in the transition into the steady-state conditions is shown in Figure 12. The stocks and quality of stored plutonium are being gradually stabilized, and the reactor system will stop accumulating plutonium.

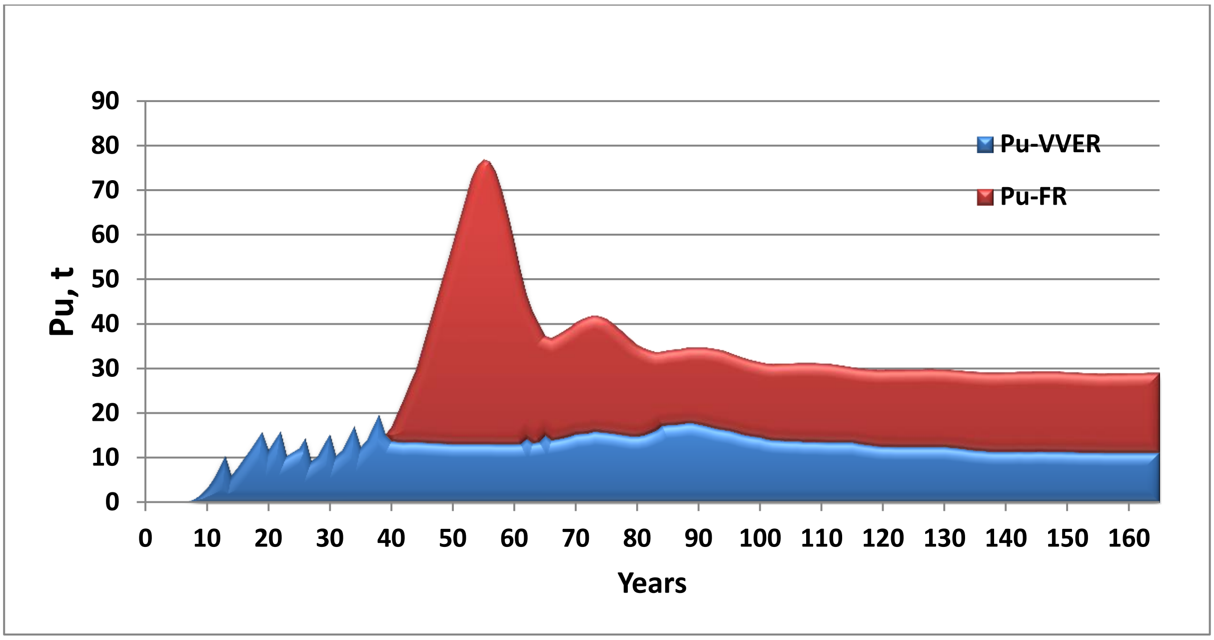

FIG. 12. Dynamics of plutonium stocks in the transition into the steady-state conditions.

Figure 13 shows approximate isotopic compositions of plutonium separated from MOX spent fuel assemblies (MOX-SFA) of the VVER and FR reactors with plutonium multi-recycling in the VVER and FR reactor system under consideration after cooling time.

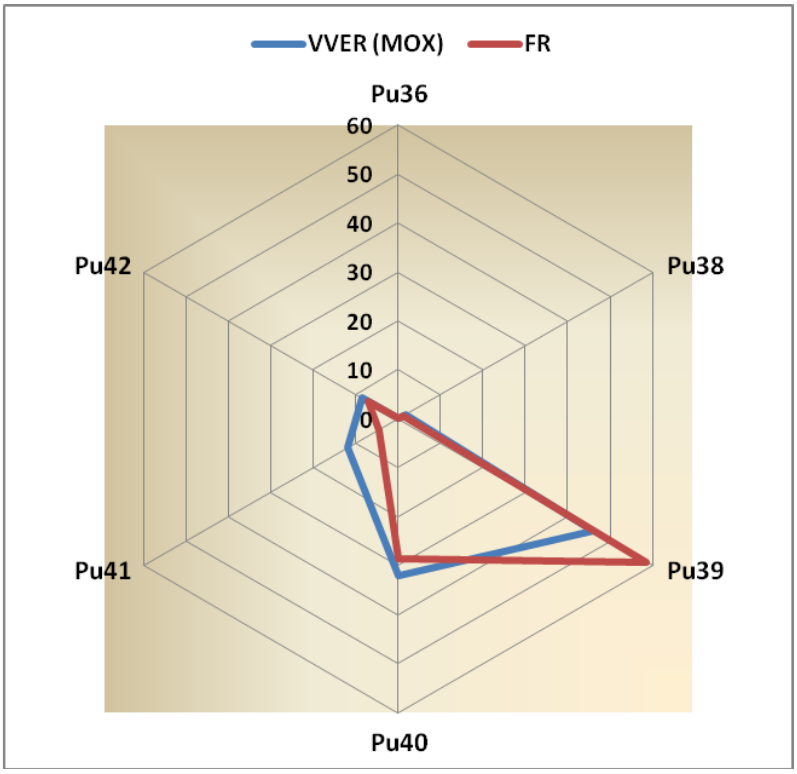

FIG. 13. Plutonium vectors obtained for MOX-SFA of VVER and FR reactors with plutonium multi-recycling in the system under consideration.

6. Conclusions

As a result of computational research of the transition of the two-component system consisting of VVER and FR reactors into the equilibrium mode of operation in the closed FC, it was found, that:

- The FR share in the system is roughly 37%.
- The use of fast reactors allows SNF accumulation in the scenarios to be reduced by 47% in (2), by 92% in (3), FR + VVER transition to MOX - by 100% - (4).
- Annual consumption of natural uranium in the steady-state conditions is reduced by a factor of 2.6 as compared to ONFC.
- Introduction of the FR into the system and arranged exchange of plutonium of different quality between thermal and fast reactors allows plutonium isotopic composition degradation to be stopped under the conditions of plutonium multi-recycling, and plutonium content in the VVER reactor fuel to be provided within tolerable limits.
- The two-component nuclear power system analyzed can serve as a model of stationary nuclear power, where upon reaching a certain level of reactor installed capacity, the annual electricity production will be stabilized due to lack of demand for its increase,

as well as the model of a certain module, having the above positive qualities within the nuclear power.

- Under the conditions of actual nuclear power in Russia, launching a small series of fast reactors and transition of some VVERs to partial MOX-fuel load can be performed with the use of plutonium inventory available; the actual results on the reduction of SNF and produced plutonium amount can be obtained during 15-25 years.
- For the effective joint operation of reactors in the NPS, their performance may need optimization.

7. References

[1] Kalashnikov, A., Moseev, A., Dekusar, V., Korobeynikov, V., Moseev, P. “Evolution of the CYCLE Code for the System Analysis of the Nuclear Fuel Cycle”, Nuclear Energy and Technology, Volume 2, Issue 2, 2016, pp. 114-118.

[2] Le Mer J., Carzenne C, Lemasson D. France EDF Research Scenarios for Closing the Plutonium Cycle. International Conference of Fast Reactors and Related Fuel Cycles. Safe Technologies and Sustainable Scenarios FR13, 4-7 March 2013, Paris, France. Paper N IAEA-CN-199-292.