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Research Article

Economic advantages of starting up of inherently safe fast reactors with a closed fuel cycle on fortificated uranium*

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Abstract

The publication substantiates the economic advantages of using in the starting loads of inherently safe fast reactors with a closed fuel cycle of enriched uranium instead of uranium-plutonium regenerate obtained by reprocessing of thermal reactors spent nuclear fuel (SNF). The justifications are given taking into account both the preliminary technical and economic assessments carried out by the basic enterprises of TVEL JSC and SHK JSC, and the neutron-physical and system-economic studies performed at the Private Institution of the ITCP Proryv (Breakthrough). It is shown that the starting-up of a fast reactor on enriched uranium instead of uranium-plutonium fuel, taking into account the costs of preliminary reprocessing of thermal reactors spent fuel, allows achieving a significant economic gain at the stage of construction and commissioning of nuclear power plants. It is also shown that even at moderately high values of the discount coefficient, the uranium start of a fast reactor with a closed fuel cycle is economically preferable in comparison with the option of starting on uranium-plutonium fuel from the positions of the break-even tariff.

Keywords

inherently safe fast reactor, start-up with enriched uranium, levelized cost of electricity, economics

Introduction

Since the beginning of the 20th century, the developing world has been aiming to increase substantially the level of per capita electricity consumption. But the evolution of conventional sources of electricity is limited fundamentally due to the depletion of fuel resources and involves large-scale emissions of hydrocarbon combustion products, thus reducing the potential of conventional generation against the background of nuclear power (NP), the sources of raw material for which, in the event of the reactor fleet deployment based on resource saving fast nuclear reactors (NR), become practically inexhaustible. Thermal reactors (TR), on the base of which nuclear generation was historically developed due to an initial goal-setting error, are known to lack the potential for addressing the entirety of energy-scale issues (economy, full utilization of uranium, nonproliferation, waste).

Initially and throughout their evolution process, fast reactors were designed to achieve high rates of plutonium breeding (by forcing the breeding ratio (BR) and power density), which affects detrimentally the NR safety and economic performance. The high breeding requirements were imposed by the method selected for starting up fast reactors

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(using plutonium from the TR spent nuclear fuel (SNF)[1]); otherwise, it would not be possible to develop large-scale NP based on FRs at a pace the developing world has been trying to achieve through the 20th and 21st centuries onwards.

The core of the pilot and demonstration fast reactor (BREST) under construction at SHK JSC's site is characterized by moderate BR and power density values. This has made it possible to ensure the reactor's high immunity to severe accidents owing to the natural qualities and regularities inherent in its design (primarily, negative reactor power and fuel/coolant temperature feedbacks) (Adamov et al. 1997). As a result, such reactors can be reasonable referred to as nature-like (meaning that nuclear power is characterized by the smallest lifetime carbon trace as compared with other energy generation types), or ISFR. 'Nature-like' means also the availability of a closed nuclear fuel cycle that excludes accumulation of large quantities of radioactive waste (RW), which are absent in nature and believed to be the major problem unsolved through the evolution history of nuclear power.

Russia is the world's acknowledged leader in the field of fast reactor technologies, operating the planet's only commercial fast reactors, BN-600 and BN-800. There are several lead-cooled fast reactor research centers in the world (Alemberti et al. 2020). Romania, for instance, intends to build a fast neutron reactor, the ALFRED (Alemberti et al. 2013; Tarantino 2021) in the core of which, however, it's planned to use mixed oxide fuel, which is noticeably less dense and heat conductive than mononitride used in the BREST-OD-300, thus making it impossible to ensure a small reactivity margin for the cycle between refueling and achieve the safety level inherent in the Russian reactor developed as part of the Proryv project. Belgium plans to commission the MYRRHA multipurpose hybrid research reactor for high-technology applications with an external neutron acceleration source (Abderrahim et al. 2010; Dorochova 2020). Along with oxide fuel, however, the reactor uses lead-bismuth coolant. Neutron irradiation of Bi gives rise to radiotoxic polonium-210, which emits high-energy alpha radiation. Uranium oxide fuel and lead-bismuth coolant are proposed for use in small fast reactors: URANUS (South Korea, Shin et al. 2015) and CLEAR (China, Pengcheng et al. 2013).

With a focus on addressing safety issues, the fast NR technology developed within the frameworks of the Proryv project is expected to lead to mitigated design and operating regulations for new NPPs (Varshavsky 2013) and, as a sequence, to their improved economic performance. It is possible to build large-scale power based on such reactors at a pace that allows developing countries to get substantially closer to the leading ones by the level of per capita energy consumption as soon as in this century, only by starting of these on enriched uranium, U_{enrich}, which allows to substantially economize the natural uranium (U_{natur}) consumption for the reactor startup.

The pronounced strategic advantages of starting up of inherently safe fast reactors with a closed NFC on enriched uranium were confirmed at the FR-17 international forum by Orlov 2017. It was also there (as well as in Orlov 2018a) that, along with the confirmation that inherently safe fast NRs can be started up on enriched uranium, there were assumptions made regarding the economic efficiency of this closed NFC option not only in distant but also in the near future.

These predictions are justified since it is not accidental that most of the world's nuclear fleet (total power of ~400 GW) operates on enriched uranium fuel. These assumptions were confirmed in Orlov 2018b where the system-economic calculation results were presented for Russian NP with regard for its prehistory (existence of fuel and reprocessing facilities, sublimation and separation facilities, RW storage points, etc.). These calculations took into account a large number of nuances, including availability of warehoused resources of Pu (45 t of reactor-grade and 50 t of weapon-grade plutonium) and highly enriched uranium (Podvig et al. 2017), and the anticipated commissioning of centralized reprocessing facilities (the PDC, etc.), complicating, to a certain extent, the insight into the essence of the problem, while not affecting in a meaningful way the conclusions made with respect to the economic justifiability of using enriched uranium fuel in the initial loads of the first industrial energy complexes (IEC). This publication provides a more graphic conceptual proof for the economic viability of the fast NR startup on enriched uranium without focusing attention on multiple nuances of system-strategic simulation, listed mostly in Orlov 2018b (but in some cases, not reflected in Orlov 2018b, this paper presents additional specifying comments).

Preliminary technical-economic and neutronic studies

For a number of reasons, the pilot fabrication and refabrication module (FRM) of the pilot and demonstration energy complex (PDEC) uses a carbothermic synthesis technology (CST) to fabricate mixed nitride uranium-plutonium (MNUP) fuel. In particular, this is explained by the fact that both plutonium from the TR SNF for production of the starting load and regenerated fuel material (after the hydrometallurgical reprocessing) will be supplied to the PDEC NFC's fabrication stage in an oxide form which is initial exactly for the CST method. At the same time, as noted in Orlov 2018b, it is reasonable to use a compact high-efficiency method of direct fuel powder synthesis for production of initial FR loads based on uranium fuel (Reshetnikov et al. 1973; Rogozkin et al. 2003; Rogozkin et al. 2011).

A number of inquiries were made to different specialized organizations to check the assumptions about the economic efficiency of the fast reactor startup on enriched uranium. Experts at TVEL JSC, based on the initial data they were provided for the core design started on the fast NR enriched uranium, have estimated the capital costs

1 We shall note that SNF from the world's most widespread light-water reactors contains some 1% of Pu

of building the 'nitride' line at one of the existing fuel plants to be smaller than those for the PDEC FRM production facilities. Employees at SHK JSC have provided the estimates for the cost of equipment for the uranium fuel fabrication by direct hydrogenation/nitration method, and estimated the operating costs. The price parameters of the uranium fuel fabrication using the above method have also proved to be optimistic against the background of the cost indicators for the uranium-plutonium nitride production using the CST technique.

The fuel balances for the case of the commercial fast NR startup on enriched uranium fuel with further operation in a closed NFC were calculated as part of previous neutronic studies (Orlov 2017, 2018a), during which an earlier stereotype (see, e.g., Volkov et al. 2016) was dispelled accordingly to that it was excessively difficult, in technological terms, to comply, throughout the lifecycle of a fast reactor started up on uranium, with the fundamental inherent safety requirement of ensuring a small reactivity deviation (comparable with the effective fraction of delayed neutrons) from the equilibrium value (Adamov et al. 2017). Optimization calculations have shown that is it possible to simplify considerably the mode of transition from the starting uranium to the equilibrium uranium-plutonium cycle with a Pu fraction of ~ 14% (as the content of the Pu fraction in fuel is increased). While it was proposed in earlier studies that such approach was to be undertaken in several iterations, it was shown in Orlov 2017, 2018a that it was possible to use a simpler transition by way of a double or even single change in the process of the reactor operation (with these changes becoming more technologically effective). This result has proved to be possible due to the fact that in Orlov 2017, 2018a, unlike earlier studies (e.g. Orlov et al. 2013), the evolution of the fuel's isotopic composition was calculated with detailed simulation of partial refueling (with regard for the NFC reprocessing stages with a multiple recycle of fuel at the SNF reprocessing facility and the fabrication and refabrication module in conditions of switchover to an equilibrium mode of operation), which has allowed mitigating the core neutronic performance requirements against the options considered earlier in which refueling was cycle-based. Calculations in Orlov 2017, 2018a showed the feasibility of reducing the weight of the starting load and the fuel regenerated in partial refueling, as well as of increasing its specific burnup depth as compared with the earlier proposed uranium startup options for inherently safe fast reactors. Specifically, as the result of this activity, four know-how practices were validated, in which, taking into account recent surveys by base institutes (Lizunov and Solodov 2015), an option was also considered with the fuel load neutronic performance managed by varying the nitride NF ^{15}N isotope fortification (Orlov 2018a).

We shall also note the following circumstance. In terms of neutronic performance, uranium fuel is the farthest from equilibrium one against the background of any (even low-background) uranium-plutonium fuel, so justification for the possibility to provide the acceptable reactivity margin for ISFR throughout the period of its operation with the uranium startup means that such possibility exists even more so in the event of the reactor startup on mixed fuel with plutonium of arbitrary isotope composition. In Orlov 2018a, the "omnivorousness" of a fast reactor with respect to plutonium with any isotope composition was proved as well by a direct calculation (in addition to the base result, bearing in mind that the uranium-plutonium start, unlike the uranium one, fails to open up the potential for evolution in the current century of power engineering the whole world requires for achieving per capita energy consumption as in the Golden Billion countries).

Demonstration of a substantial gain in initial costs with the enriched uranium startup of an inherently safe fast reactor

It's easy to verify that the startup of inherently safe fast NR operating in a closed NFC based on enriched uranium instead of uranium-plutonium fuel obtained by the TR SNF reprocessing leads to a substantial economic gain achieved at the initial stage; this requires just to compare the structures of the costs per unit for the NR starting load production in the above two cases.

Actually, the startup of a fast reactor on enriched natural uranium necessarily involves the cost of its mining, conversion (a minor contributor to the aggregate cost of NF), enrichment, transformation of uranium hexafluoride into tetrafluoride, reduction of uranium tetrafluoride to metal, and fuel fabrication. As to the natural uranium mining and isotope separation procedures, these have become more profitable against the background of the Fukushima events (Orlov 2018b; UxC Prices 2022).

Being pyrophoric, nitride fuel is characterized by higher fabrication costs, as compared with those for oxide, but, as was already mentioned, using the direct hydrogenation/nitration method to fabricate the starting uranium load for a fast NR, with regard for the radiation safety of uranium fuel, as estimated by SHK JSC's experts, leads to a substantial economic gain as compared with the initial load fabrication option based on high-background MNUP fuel using the CST method.

The fast NR startup on enriched uranium leaves an unprocessed amount of TR SNF (about 1 kiloton) which would be required in the reactor MNUP startup option to provide its initial loading with the desired quantity of plutonium. Accordingly, estimating the costs of producing initial uranium loads for fast NRs also needs to take into account the cost of storing this unprocessed SNF. Fig. 1a, b present the structures of the costs for fabricating the starting uranium load for a fast NR. For certainty, pressurized water power reactors (VVER) are considered in the figures as TRs.

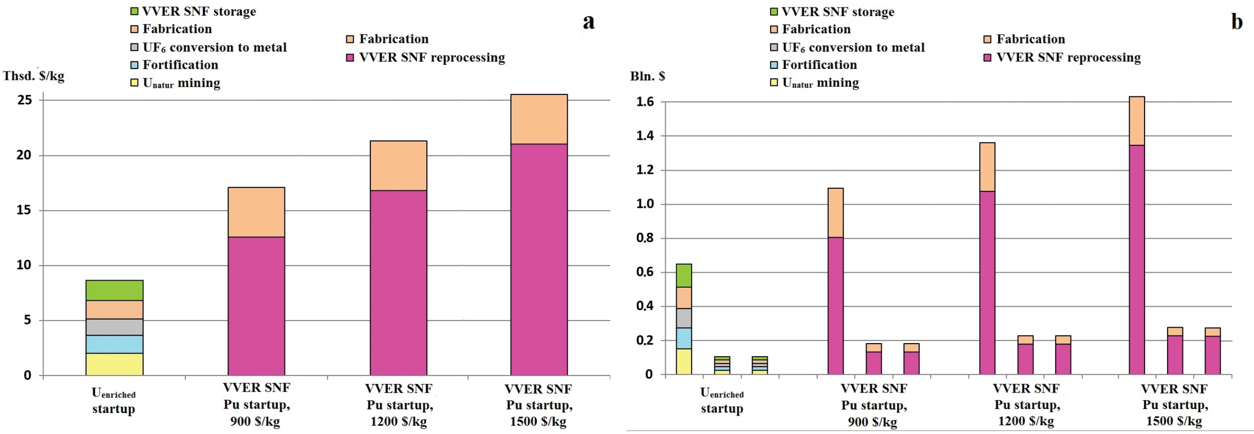

Figure 1. Costs of producing the IEC initial load based on enriched uranium or plutonium obtained as a result of the VVER SNF reprocessing **a.** cost per unit; **b.** absolute costs (with regard for the makeup fuel batches for the two initial partial refuelings). Contributions: 1 – VVER SNF storage; 2 – fabrication; 3 – UF_6 converted to metal; 4 – enrichment; 5 – U_{natur} mining; 6 – VVER SNF reprocessing.

Meanwhile, if all of the above operations required for the fast NR starting uranium load fabrication can be realized, in total, in the course of a decade, the storage of TR SNF takes evidently place in future as well, thus the storage costs need to be estimated with regard for the discount factor. For certainty and conservatively, the figures present the absolute costs of storing the unprocessed amount of TR SNF for 15 years.

As to the option with the fast NR startup on uranium-plutonium fuel, the cost per unit for the initial load production represents the combined costs of the thermal reactor SNF reprocessing (with regard for all stages of the full SNF handling lifecycle) and the NF fabrication cost.

Producing 1 kg of uranium-plutonium regenerate for the fast NR fuel requires, in a first approximation, reprocessing the amount of TR SNF larger by a factor of 14[2] (in total, ~1000 t for the starting load fabrication). And the cost per unit for reprocessing, with regard for all related operations, as estimated by the MIT, can reach ~ 1500 $/kg (The Future of Nuclear Power 2003; The Future of the Nuclear Fuel Cycle 2011).

Storage of TR SNF is not expensive (~ 8$/kg per year), due to which its reprocessing to date has not been spread worldwide. This has led to rather a marked difference in its price indicators (they depend on productivity and the actual volume of the reprocessing plant's work load, the share of conditionally fixed costs, technologies and hardware used for production, cost indicators for individual stages of the TR SNF complete handling cycle, etc.). One should bear in mind that the cumulative TR SNF costs also include the expenses of temporary SNF storage, transportation and intermediate storage and vitrification of high-level waste (in total, these costs may reach ~ 250 $/kg).

Since manufacturing of 1 kg of uranium-plutonium fuel for an FR will require reprocessing ~ 14 kg of TR SNF, the cost per unit for obtaining fresh U-Pu raw product (from reprocessing of outside rather than in-house SNF) for the FR fuel fabrication equals ~ 12.6 thsd. $/kg and 21 thsd. $/kg with the TR SNF handling cost being 900 $/kg and 1500 $/kg respectively.

The cost per unit for the MNUP fuel fabrication (including the RW handling deductions), based on the competiveness requirements, is assumed to be equal to ~ 4.5 thsd. $/kg. Therefore, the basic costs, in the event of the starting load production based on uranium-plutonium fuel, need to be attributed to the TR SNF reprocessing.

Column 1 in Fig. 1a presents the structure of the costs per unit for the fabrication of the starting uranium load for a fast NR, and further columns, up to the fourth one, illustrate the structure of the cost of producing the initial uranium-plutonium load (in cases when the cost per unit for the TR SNF reprocessing is equal to 900, 1200 and 1500 $/kg respectively). Fig. 1b presents a similar comparison for the absolute costs of the fast NF starting load fabrication with regard for the initial makeup fuel batches. It can be seen that the uranium startup allows achieving a substantial economic gain at the starting fuel batch fabrication stage (with regard for a larger neutron yield for fission and a smaller absorption cross-section in the fast NR spectrum for ^{239}Pu, as compared with ^{235}U, and, accordingly, a larger weight of the uranium load relative to the uranium-plutonium one), primarily due to rather a substantial contribution of the thermal reactor SNF reprocessing expenses to the cumulative fuel costs for an NR started based on MNUP fuel.

It should be noted that, if the costs of developing fast and thermal NR capacity are considered individually, an approach exists (and appears to be fairly justified) which suggests that the costs of the TR SNF reprocessing shall be reasonably fixed mostly with the fast reactor fleet since this reprocessing, in the event these reactors are started up on U-Pu fuel, is necessary for generation of Pu to form the starting loads for exactly fast NRs. And as to the TR SNF storage costs, these shall be evidently justifiably fixed with the TR fleet.

2 As noted, TR SNF contains ~ 1% Pu, in which, in addition, the ^{241}Pu isotope decays rather intensively, while the concentration of reactor-grade Pu in fuel of a fast NR operating in an equilibrium mode reaches ~ 14%.

Therefore, using uranium fuel in the starting loads for ISFR makes it possible to improve the competitiveness of the fast NR fleet against the background of thermal reactors. It should be noted that the startup of inherently safe fast NRs on enriched uranium allows mitigating the imperative competitiveness requirements towards such reactors in terms of the MNUP fuel fabrication cost in case these requirements will be hard to meet for any reasons.

The next paragraph will analyze the differences in the cost of the nuclear fuel cycle for a fast NR started up on U_{enrich} and U-Pu fuel in a partial refueling mode when the reactor is functioning with its own regenerated fuel.

As the reserves of natural uranium are depleted, it is expected to become more expensive, but, as can be seen in Fig. 1, for one thing, the economic gain with the starting load fabrication using U_{enrich} instead of the TR SNF U-Pu regenerate is rather high all the same, and, for another thing, as the past decade shows, the cost of the natural uranium mining (as well as of separation work) is defined largely by the political environment rather than by limited resources.

Justification of economic advantages from the fast NR uranium startup with regard for the costs of transition to equilibrium uranium-plutonium fuel

We shall consider the stage of transition from the starting load to steady-state reactor operation with a quasi-equilibrium fuel composition. This type is characterized by a large number of nuances. The startup of a fast NR operating in a CNFC based on U_{enrich} is known to involve a transitional period in the course of which the isotopic composition of fuel undergoes major changes (Orlov 2017, 2018a). To meet the requirements with respect to the reactivity margin during regular refueling periods, it was proposed specifically in Orlov 2017, 2018a to limit in some measure fuel burnup at the transitional stage as compared with its value in the steady-state mode (the optimal refueling strategy, in technical and economic terms, was proposed to be defined in the course of further in-depth studies).

In the event of a fast NR started up on MNUP fuel with an equilibrium isotopic composition (producing which requires long-term pre-reprocessing TR SNF cooling for ~ 25 years), the transitional period duration can be assumed to be small (several years). The average fuel burnup in this case can be assumed to be equal to its optimal value reached in the steady-state reactor operation mode as soon as after the initial fuel cycle. To date, the target value of the average burnup depth planned to be reached in the long run for the fast NR nitride fuel is assumed to be equal to ~ 12% h.a. (which corresponds to the refueling cycle duration of ~ 500 eff. days). With the fast NR startup on enriched uranium, as noted above, there is initially a transitional period in the course of which the starting uranium fuel transforms into equilibrium uranium-plutonium fuel, and it was proposed in (Orlov 2018a) to keep the interval between partial refuelings at this transitional stage at a level of ~ 400 to 440 eff. days (and the whole of this period takes ~ 15 to 20 cycles between refueling).

For certainty, we shall assume that all operations to fabricate nitride fuel for a fast NR (see Fig. 1) in each of the considered cases (with the reactor startup on U_{enrich} or U-Pu fuel) take five years in total (provided it is possible to perform these in parallel). We shall assume the external fuel cycle to be equal to two years, so reprocessing of the fast NR's own fuel and refabrication of nitride fuel starts, in the simplest case, two years after the reactor startup.

A certain reduction in the burnup depth in the event of the fast NR startup on U_{enrich} instead of U-Pu fuel means that fuel will be reprocessed and refabricated more often, and the increase in the initial load weight for the U_{enrich}-based startup leads to a growth in the volume of these operations. It is however important to bear in mind that fuel is reprocessed and refabricated with a time delay against the starting load fabrication procedure and, with regard for the discount, their contribution to the cumulative fuel expenditures decreases.

As to reprocessing of the fast NR SNF, it is important to understand that its cost, in a first approximation, is proportional to the inventory of the fission products accumulated in fuel, and the content of these in the SNF unloaded for the lifetime is proportional to the fuel burnup depth. A certain growth in the fuel load weight in the event of the uranium fuel startup leads to a decrease in the reactor core power density and, therefore, in the fission product accumulation rate. So, the costs of reprocessing SNF of a fast NR, in the event of its startup with uranium fuel instead of uranium-plutonium one, change slightly in the transitional mode.

However, due to the refabrication procedure becoming more frequent and a certain growth in the inventory of the fast NR fuel regenerated during the process of partial refueling, its production costs increase as well. Fig. 2a presents the compared NFC costs for the lifetime of a fast reactor (assumed to be equal to 60 years; storage of unprocessed TR SNF in the fast NR uranium startup option is considered for the same period of time) in the event of its uranium and U-PU fuel startup with a discount factor of 5% per annum. It can be seen that the initial stage economy overweighs the loss caused by a certain decrease in the fuel burnup and a growth in the initial load weight when the TR SNF reprocessing costs exceeds ~ 900 \$/kg.

More substantial economic advantages are achieved with a higher discount factor (Fig. 2b presents an example for the discount rate of 10% per annum) for apparent reasons: the uranium startup makes it possible to achieve a major economy exactly in the starting period which is the most important one in terms of discounting.

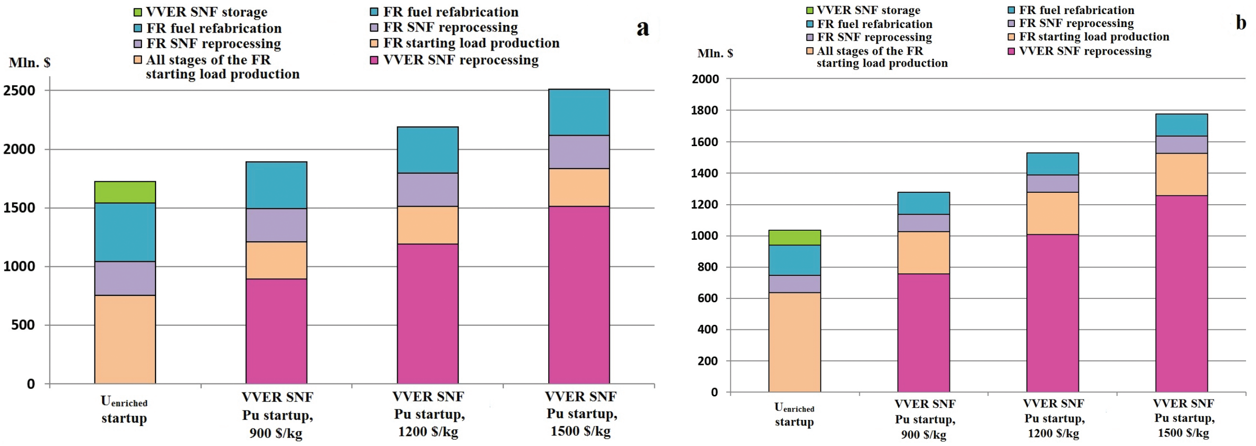

Figure 2. Comparison of the total costs for a closed NFC of inherently safe fast reactor in startup options with enriched uranium and U-Pu fuel as a function of the cost per unit for VVER SNF reprocessing with discount rates of 5% (**a**), and 10% (**b**). Contributions: 1 – VVER SNF storage; 2 – FR fuel refabrication; 3 – FR SNF reprocessing; 4 – all stages of the FR starting load production; 5 – VVER SNF reprocessing.

Fig. 3 presents the gain, δ, as a percentage of the total discounted costs for the startup of the energy complex as the whole and of the fuel costs with the inherently safe fast NR startup on enriched uranium instead of U-Pu fuel depending on the VVER SNF reprocessing cost in such volume as required for the accumulation of plutonium for the NR starting load in the second case.

It is important to bear in mind that, as noted in Orlov 2018a, the requirement for the prior long-term SNF cooling slows down the evolution rates of NP based on inherently safe fast NRs. Actually, the evolution of large-scale NP based on such reactors (characterized by moderate power density and BR values) in the event of their startup on U-Pu fuel demands mitigating the requirements for the TR SNF cooling time; in this case, fuel will contain more of the ^{241}Pu fissionable isotope, the intensive decay of which will lead to a growth in the absolute value of the negative reactivity runout, and it is also reasonable to limit burnup at the initial stage (the most noticeable in discounting terms) for neutralizing this effect. A similar problem arises when weapon-grade plutonium is used in the fast NR starting load due to the ^{240}Pu isotope (with a relatively small neutron capture cross-section) being absent in it and accumulated further (Orlov 2018a).

It is proposed in some publications that the problem in question may be resolved, specifically, by adding minor actinides left from the TR SNF reprocessing to the starting load. However, it is important to bear in mind that the FC involving americium, which is more highly radioactive than plutonium, leads to more expensive fabrication of the fuel load due to the need for upgrading the radiation safety systems (and neptunium shall be reserved for being massively used in the starting loads of fast NRs). No detailed study has been undertaken to date with respect to the methods to ensure a small reactivity margin with the FR startup on U-Pu fuel with an non-equilibrium isotope composition.

There are nuances other than dealt with in this paragraph, but they do not have a fundamental effect on the result.

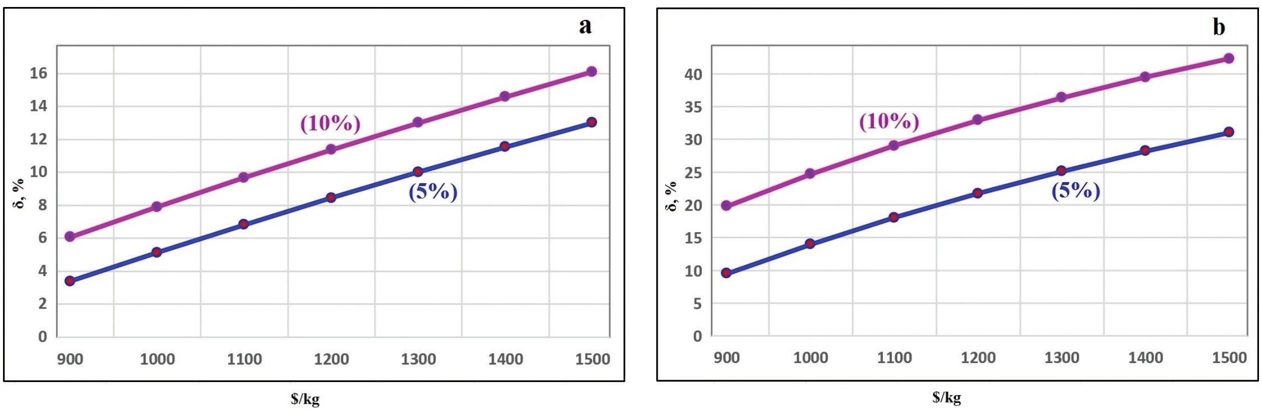

Figure 3. Relative percentage gain, δ, with discount rates of 5% and 10% in the event of the naturally safe fast NR startup on enriched uranium instead of uranium-plutonium fuel as a function of the cost per unit for the VVER SNF reprocessing **a.** in total reduced costs of the IEC construction and operation based on an inherently safe reactor facility; **b.** in reduced costs of a closed NFC.

Conclusions

The estimates obtained by leading Russian organizations within Rosatom State Corporation's fuel division for the costs of producing initial uranium loads for fast NRs with inherent safety properties, combined with the neutronic and strategic systems studies undertaken as part of the Proryv Project, have confirmed the assumptions made at the FR-17 Conference (Russia, Yekaterinburg, Sverdlovsk Oblast) that revolutionize modern approaches to formulating the strategy for deploying world's NP: nature-like nuclear reactors need to be started, not only for strategic reasons but also in terms of cost effectiveness, based on fuel provided to humankind by nature as such (that is, enriched uranium fuel) rather than on artificial fuel mixed with a transuranic element (plutonium) which is absent in nature due to being radiotoxic. And it is reasonable to use direct hydrogenation/nitration method, the most "direct" technique for obtaining nitride fuel powder, to produce the starting batch of NF.

Specifically, evidences were obtained to prove that the uranium startup, even with moderate discount rates (over ~ 5%) and VVER SNF reprocessing cost values (which, according to different sources, can reach ~ 1500 $/kg), is a factor of improving the economic performance of fast NRs in terms of levelized cost of electricity. It was believed earlier that NP was losing its competitiveness, as compared with other electricity generation types, with high discount rates. The findings, in terms of economic advantages from the startup on enriched uranium fuel, extend the competitiveness boundaries of NP based on inherently safe fast reactors, making it so possible to increase the maximum discount rate, with which the commissioning of a fast NR, operating in a closed NFC, instead of a conservative TR (that does not resolve the combination of issues involved in the full use of the NF energy potential, emergency safety, economy, spent fuel, etc.), as well as of renewable energy sources and conventional sources of electricity, turns out to be economically reasonable.

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