Possible scenarios of transition to the closed nuclear fuel cycle

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Abstract. This work is devoted to the comparative analysis of various scenarios of transition to introduction of the closed nuclear fuel cycle and sodium fast reactors in nuclear power of Russia. The analysis of the permissible scale of introduction of water-water power reactors and fast sodium reactors into the Russian nuclear power system was carried out taking into account the estimated reserves of natural uranium, the expected volumes of spent nuclear fuel from both national and foreign nuclear power plants and the quantity of plutonium available for the introduction of fast sodium reactors. The rate of growth in the capacity of the nuclear power system is not yet high, the resources of natural uranium seem significant, the natural uranium mining facilities and the amount of depleted uranium have not yet been classified as encumbrances. In the current situation, the practical solution to the problems of closing the nuclear fuel cycle and transition to the trajectory of development of nuclear energy as a system that meets in the future the requirements of sustainable development and energy security can already be started with the use of mixed uranium-plutonium oxide fuel in combination with fuel from enriched regenerated uranium in existing water-water power reactors and in BN-800. This step is the most promising in terms of minimizing contradictions between the existing legal and institutional framework, allowing the development of closed fuel cycle technology and reducing the amount of spent nuclear fuel. Based on the assessment of the technical and economic characteristics of various scenarios for the long-term development of the two-component nuclear power system in Russia, several possibilities for reducing the cost of implementing the transition stage from open to closed nuclear fuel cycle.

1. Introduction

Nuclear Power Industry (NPI) is the important segment in the economic, energy and innovational development of Russia and allows ensuring energy safety and stable development of the country’s economy in the long-term perspective, robust solving the greenhouse gases emission problem, and increasing of the share of exported high-tech and science-intensive products. Urgent nuclear power industry problems are as follows: safe operation of existing NPI facilities; creation of effective and safe nuclear power sources of Generation 4; transition to the closed nuclear fuel cycle (NFC) in order to minimize the volume of the stored spent fuel (SF) and reliable supply of reactors with the fuel resulted by means of production of fissionable isotopes due to breeding on fertile uranium-238 and thorium-232; safe management of radioactive wastes (RW); implementation of safeguards against unauthorized proliferation of nuclear materials. After these problems have been solved, the nuclear power production will acquire completely new properties with the diversification of the product basket. Here, any innovations, inventions and alternative technical solutions must be built in the
already established nuclear power system, which includes both evolutionary and innovational installations and structures of already existing nuclear industry.

Closure of the nuclear fuel cycle and transition of the two-component nuclear power industry to the fuel self-provision will let it satisfy the requirements to renewable energy sources, with respect to which priority development conditions are being created in the power segment. The sooner the ability of fuel self-provision is realized in Russian nuclear energy system, the higher the industry involvement potential at the nuclear technologies market will be. To solve this task in the XXI century, both the development of the fast-neutron reactor technologies with the minimal initial load and high excessive fuel breeding, and realization of the possibility of efficient work of thermal reactors in the closed fuel cycle with the increased fuel breeding.

A series of studies carried out under international INPRO and Generation 4 projects showed that creation of profitable business in the SF processing, plutonium use and RW handling by means of innovations with the participation of entrepreneurs and private saving without states’ involvement, is almost impossible. The same relates to implementation of fast-neutron reactors [1,2].

Transition to the closed nuclear fuel cycle includes refinement of the closed fuel cycle technologies components and the system analysis of potential scenarios of this transition in order to determine the nuclear power industry structure, which minimizes the risks associated with its functioning, as well as significant uncertainty of the innovational technological development and resource procurement perspectives. Such targeted and meaningful planning of the nuclear power industry requires targeted and comprehensive R&D, incommensurable to the today’s research and development scale. The successful solution of these problems is impossible without significant depth and volume of fundamental research, which today is a historical challenge to nuclear science and technology.

Russia is experienced in SF industrial processing with the application of the water chemical technology, here new modern technologies, which minimize the RW generation volume, are being developed and implemented. It is planned to duplicate the integral capacity of the SF processing facilities during the period up to 2030 [3-5]. The uranium regenerated during processing is used in production of fresh fuel for RMBK and VVER reactors. Production technologies are being developed: tablet REMIX-fuel - on the basis of the non-separated mixture of regenerated plutonium and uranium oxides; MOX-fuel - on the basis of the mixture of plutonium and depleted uranium; mixed tablet nitride fuel. The first experience of irradiation of experimental fuel pins with REMIX-fuel was obtained at VVER-1000 reactor of Balakovo Nuclear Power Plant (NPP). Key experience of application of the power plutonium regenerated from SF processing will be obtained in the course of production and irradiation of MOX-fuel in BN-800 reactor. The facility built for production of MOX-fuel for the power unit with BN-800 reactor is at the stage of set up and reaching the project capacity. There are more than 50 tons of civil plutonium regenerated from commercial reactors SF stored at warehouses. Despite the fact that Russia is one of the world leaders in development of technology of fast spectrum reactors neutrons, their share in the system of the nuclear power industry of the Russian Federation may become significant only in the second half of the XXI century. The basis of the existing and planned for the construction of the reactor Park of the domestic nuclear power plant is the existing and under construction water-water pressurized power reactors with a thermal spectrum of neutrons of the VVER type.

The use of the mixed uranium and plutonium fuel in VVER-TOI, VVER-S, VVER-SKD may improve technical and economic indicators of light-water reactor NFC, reduce the risks of the nuclear power industry development long-term development by means of decreasing growing expenses for SF storage, ensure a technological solution for application of uranium and plutonium regenerated from SF processing under the conditions of NFC closure. Fast neutron reactors have not been implemented in any significant scale, which limits increase of the natural uranium efficiency increase. NPI capacity growth rates are not high, natural uranium resources (if we show no perspective of NPI supply with fuel in the second half of this century) seem to be endless, the future of extractive facilities and the waste uranium quantity have not been classified as a burden yet. In this situation, the practical solution of the NFC closure tasks and transition to the NPI development path as the system, which in
perspective will meet the requirements of sustainable development and capable of making a significant contribution to solving the power safety problem, we may begin to use REMIX and/or MOX fuel in existing VVER and BN-800 reactors even now [6-20]. This step is the most perspective in terms of minimizing controversies between the existing legal and institutional basis and allows for development of the closed NFC technology. By accumulating the experience of use of plutonium in the closed NFC for VVER and BN-800 reactors, new developments of necessary references for existing innovations in the legal and institutional spheres, which are required to form conditions for efficient and reliable functioning of economic mechanisms with necessary elaboration of the liability issues and ownership rights to radionuclides, which will be present in the NPI system in significant quantities during the time period, which duration in principle prevents the current economic system to minimize uncertainties to the level acceptable for reliable system operation. It is likely that only after this stage it will be possible to make a reasoned choice of fast neutron reactor (FR) parameters necessary to solve the problems of sustainable development. But in the time that remains before the decision to start a large-scale introduction of FR into the NPI system, much needs to be prepared and developed, to accumulate the necessary resources, in particular, in terms of the development of models, principles, theoretical concepts necessary for the adequate formulation of the problem, without which the adoption of an important decision in conditions of considerable uncertainty on many important conditions and parameters becomes very risky.

The technology of sodium fast neutron reactor (SFR(BN)) is the most prepared one for industrial FR implementation in the mid-term perspective. This work is dedicated to the comparative analysis of various potential scenarios of transition to the closed NFC and SFR implementation in the NPI of the Russian Federation. Based on the estimate feasibility studies of various scenarios of the long-term development of the two-component NPI system in Russia, several possibilities of reduction of costs for implementation of the NPI system development transition stage from the open NFC to the closed NFC following implementation of SFR. For the adequate analysis of the technologies possibilities in the NPI, it is necessary to consider significant time intervals as the service life of current power unit projects is 60-80 years. The works considers the time period of the NPI system development in Russia till 2100. The role of the reactor technology, and, therefore, key requirements there to may be changed in time and based on the transformation of the NPI system structure. An analysis of the allowed scale of VVER and SFR development under the conditions of restricted natural uranium reserves in Russia was carried out taking into account the expected SF volumes from both national and foreign NPP and corresponding available volumes of plutonium for implementation of SFR.

2. The scenario analysis of Russian NPI long-term development

2.1. Initial restrictions, scenarios and tasks selected for the study

The key task of this work is to show on the basis of the comparative analysis of scenario variants of the NPI system development the borders of technologies implementation and to formulate the requirements to the BN-1200 reactor technology, as well as to obtain characteristics of the NPI system, which are important from the point of view of drawing up proposals and recommendations for a stage-by-stage transition to the closed NFC.

For the period after 2050, the increase in the integrated capacity of the nuclear power system is made according to the trend set by the actual state of the system and the roadmap under consideration from 2018 to 2050. Under this assumption, by the end of the century, the installed capacity of nuclear power will reach ~73 GW(e), provided that the blocks that have developed their resource are replaced by new power units.

The solution to the problem of processing of SNF by RBMK should be evenly distributed over time, taking into account the minimization of the impact on system indicators.

In determination of the economic efficiency of implementation of BN-1200 reactor technology in Russian NPI system, it is insufficient to rely on the results of calculations of competitiveness parameters specific for each power unit. The conclusion about the competitiveness of technology
should be done, with a view to determining the place and role of BN in the nuclear power system. The role of the reactor technology, and, therefore, key requirements there to may be changed in time and based on the transformation of the NPI system structure. Determination and comparative analysis of the fuel component of the cost of electricity produced for the BN-1200 and VVER-TOI reactors does not allow to see the dynamics of fuel costs in the nuclear power, taking into account the time, schedule of input/output capacity, infrastructure development NFC. In order to assess financial indicators, it is vital to understand the dynamics of changes in the current expenses related to the nuclear fuel cycle arrangement, which may be evaluated as the relation of the current cost of the initial and end stage of the fuel cycle to the electric power produced at the specific period of time, which in CFC and LCOE are allocated in time.

The cost fuel component \((C_T)\) shall be calculated with the estimate method as the relation of the sum of expenses at each production area \((Z_i)\) in the current year to full power production \((W)\) for such year:

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C_T = \frac{\sum Z_i}{W}
\]

Elaboration of NFC infrastructure development plans must be based on the current requests by the NPI.

The comparative scenario reviews the following potential variants of NPI development:

- open NFC variant based on the VVER-1200/TOI technology with the development till 2100 in accordance with Russian power strategy project till 2035 (no industrial implementation of the fast-neutron reactor technology);
- two-component system development version with thermal and fast reactors in accordance with the scenario of input and output of power facilities up to 2050 defined at Concern Rosenergoatom, JSC (development up to 2100 is determined based on the rate of construction of BN-1200 power units set at the first stage);
- two-component system development version with thermal and fast reactors in accordance with the scenario established at Concern Rosenergoatom, JSC, of putting power facilities in and out of operation till 2050 (development till 2100 is established based on the maximum possible rate of BN-1200 power units construction);
- BN (SFR) technology possibilities in the two-component system of NPI of the Russian Federation (RF) in order to form the proposal for services of the fuel cycle for the external market.

2.2. NPI development scenario version based on VVER-1200/TOI in the open NFC

The average value of the electric power cost fuel component (CFC) systemic value in the interval from 2040 till 2100 in the open NFC is 26.5 kopeks/kW h, which by 30% exceeds previously established CFC for the VVER-TOI power unit, as it takes into account direct expenses (without) discounting and expenses for formation of start loads in the NPI system (figure 1).

Figure 1 shows that a rapid commissioning and load of processing facilities (Pilot Demonstration Facility and two RT-2 phases) in the system creates a sharp outburst of annual NFC costs (by~20%) in the middle of 20-s and 60-s. Sudden processing costs growth may be compensated with by accumulation of the funds in special reserve funds, which have undertaken SF liabilities against Concern Rosenergoatom, JSC. Processing costs are underlying in the structure of the fuel cycle annual expenses. Planning of processing facilities commissioning must rely on the long-term financial project related to SF handling. Figure 1 also shows that SF processing in the open NFC leads to significant expenses for storage of the excreted plutonium. These expenses exceed the expenses for SF storage, which plutonium was in. The cost of natural uranium will grow five-folds by 2100.
Figure 1. Cost fuel component structure by the cost type for the open NFC.

Reduction of expenses for production of fresh fuel during the interval from 2015 - 2040 is resulted from withdrawal of RMBK reactors with lower burn up parameters. Expenses for long-term RMBK SF storage make no significate contribution to the relative fuel component of the NPI system, but this leads to the deferred problem of its handling, which eventually will result in the increase of the relative fuel component in the system. Solving of the RBMK SF processing task shall be distributed evenly in time taking into account minimization of the exposure to the systemic indicators.

2.3. The two-component system development scenario version with thermal and fast reactors in accordance with the plan established at Concern Rosenergoatom, JSC, of putting power facilities in and out of operation till 2050 (development till 2100 is established based on the growth rate of BN-1200 power units construction at the first stage)

The task of the suggested scenario is assessment of the VVER technology maximum development limits taking into account reserves of natural uranium existing in the RF based on the road map of VVER and BN-1200 power units construction during the period from 2018 through 2050. The possibility of use of all natural uranium available in the NPI system allows preserving reactor diversification (with thermal and fast spectrum of neutrons) and postpone implementation of the large-scale BN-1200 power units implementation strategy under the conditions of limited experience of their operation at the first operation stage of the technology implementation (figure 2).

Figure 2. Established capacities till 2100, GW(el.) (closed NFC, VVER + BN).
The scenario presented allows assessing the number of VVER power units, which may be built taking into account the limitation for national uranium reserves (689 thous. tons) and a possibility to attract the regenerated uranium to the thermal reactor fuel cycle (saving is 16%). Based on this, the balance of introduction of fast and thermal reactors is preserved almost the same as in the road map till 2050, where VVER reactor-type share will account for 57% of the total NPI system capacity by 2100. The average value of the system CFC value from 2040 through 2100 for the two-component NPI is 25.5 kop/kWt hour, which is by 4% lower than that determined for the open SF. It should be mentioned that the average burnup of SF loaded out of BN-1200 considering screens will not exceed 50 MW*day/ kghm for the basic fuel cycle, which results in no increase of the processing unitary cost. Implementation of the full SF processing under this scenario of the NPI development in Russia results in excessive plutonium stored at the warehouse. This scenario allows for disposal of plutonium in the form of MOX/REMIX-fuel in VVER-reactors (however, this opportunity was not taken into account in this scenario calculations). Both reviewed scenarios do not allow for provision of foreign power units with natural uranium extracted on the territory of the Russian Federation.

The structure of the costfuel component for expenses at production areas and for each reactor type for the closed NFC with the maximum VVER introduction and moderate development of BN-1200 technology is given in figure 3.

![Figure 3. Cost fuel component structure by cost type (closed NFC, VVER+BN).](image)

Figure 3 shows that the cost of SF processing remains one of the underlying component of the system CFC value. With the increase of part of the BN in the NPI system the component related to the costs for natural uranium, conversion and enrichment is reduced, with the fuel production costs increase. This fact is certified with similar CFC assessments for VVER and FN power units. Expenses for plutonium storage under this scenario are lower that for the open NFC variant.

2.4. The two-component system development scenario version with thermal and fast reactors in accordance with the plan established at Concern Rosenergoatom, JSC, of putting power facilities in and out of operation till 2050 (development till 2100 is established based on the maximum possible rate of BN-1200 power units construction)

The rate of introduction rate of fast reactors limits the service life of thermal reactors built up to 2050 in accordance with the roadmap, as well as the selected scenario for the development of the integrated capacity of the nuclear power system. Despite the maximum rate of construction of BN-1200 reactors after 2050, the VVER reactor share will achieve 12% by 2100 (see figure 4). By 2100 natural uranium consumption rates will significantly decrease, and the integral value of the natural uranium extracted
from subsoil will amount to 400 thous. tons. In this situation the quantity of plutonium produced for BN-1200 is insufficient for their development due to the large initial fuel load, low fuel breeding ratio (BR) and long duplication time against the fuel cycle parameters selected in the study. It should be noted that in the variant review, not only new capacities are introduced, but also reactors put out of operation are replaced. Figure 4 shows the nuclear power industry structure corresponding to the maximum use of plutonium in BN.

![Figure 4. Established capacities till 2100, GW(el.) (closed NFC, VVER + BN, maximum).](image)

Plutonium warehouse reserves assessments demonstrate that at the border of 2090 plutonium deficit occurs in the system, which cannot be covered as all SF of national reactors will have been processed by that time. There are several ways to reduce plutonium deficit at the warehouse:

- increase of average burnup for BN-1200 fuel;
- decrease of the initial fuel load and duration of the external fuel cycle for BN-1200;
- increase of breeding parameters for the BN-1200 fuel cycle (change of layout design, use of dense fuel, application of the design for fuel assembly (FA) with the internal cartridge heterogeneity);
- use of plutonium from external sources (weapon-grade plutonium, SF from foreign reactors).

Provision of the system with the maximum plutonium quantity under the reactors reviewed is possible only in case of processing of all SF. After 2035 BN-1200 reactors introduction rate is regulated with the thermal reactors commissioned earlier, which termination prior to exhaustion of the whole allowed service life is economically unfeasible. Processing facilities capacities are introduced in such a manner that ensures full load of processing facilities. Since BN-1200 reactors are put into operation for expanded plutonium reproduction and its quality is better than that of energy grade plutonium of heat reactors, then their SF is fully processed.

The structure of the fuel component on the cost of reworks for a closed NFC with a maximum input of BN is shown in figure 5. The structure of the fuel component by expenses at production areas for the close NFC with the maximum FN introduction is given on figure 5.
The average value of the NPI CFC value from 2040 through 2100 is 24.9 kop/kWt hour, which is by 6% lower than that determined for the open NFC. Figure 5 shows that by 2100 the fuel cost structure will be determined by fast neutron reactors. No expenses associated with the plutonium storage in the system occur. The fresh fuel production costs constitute the key element of the fuel cost structure.

2.5. BN technology possibilities in the two-component system of NPI of the Russian Federation in order to form the proposal for services of the fuel cycle for the external market

If we consider NPI development scenarios in Russia in the long-term perspective, expansion of Russian nuclear technologies at the external market should be taken into account. The main objectives of global integration into foreign markets are to provide financial guarantees for construction, reduce the capital cost and construction time, maximum involvement of the customer in the project implementation, the formation of proposals in the field of training and maintenance, implementation of long-term projects in the development of the nuclear power system and ensure its full life cycle. One of proposals, which may have an impact on the decision of the customer for Russian design NPP construction, may be arrangement of the life cycle with the possibility of processing, return to the cycle of regenerated materials, compacting wastes and temporary storage of SF and RW. Repeated use of regenerated uranium in the course of the fresh fuel production for foreign customers may be guaranteed by existing technologies and experience of exploitation at Russian NPPs and allows for reduction of fuel costs (~16% saving of natural uranium). Return to the VVER fuel cycle of regenerated plutonium is possible under the proposal to use MOX/REMIX fuel, which must be economically feasible and supported with the industrial operation experience. For many countries regenerated plutonium handling may be unfavourable, leading to both more complicated fresh fuel handling and the need in assurance of NM non-proliferation. However, plutonium has the energetic potential, which may be used under the developing NPI system. Implementation of this scenario will required creation of the flexible NPI system, in which plutonium consumption in time can be regulated. At the medium construction rate of 1.5 units per year abroad till 2050, the dynamics of annual SF accumulation, where the plutonium content in this SF will amount to 350 tons, will be achieved, and by 2100 at the rate of facilities being commissioned abroad preserved, plutonium quantity will exceed 1,200 tons. These estimates reflect the maximum potential amount of foreign plutonium attraction from SF of Russian origin. Besides, the market of foreign SF exists. Of three scenarios of the NPI development in Russia reviewed above, plutonium deficiency was observed only in case of 100% commissioning of BN-1200 after 2050.

In order to ensure the possibility of attraction of plutonium at early stages of the two-component NPI system formation in Russia, it is suggested to review the following restrictions applicable to the internal NFC organization:
• deferred decision for VVER SF processing (10-15 years of non-reactor storage), which will require to provide a temporary storage facility with the capacity of around 12 thou. t.hm;
• arrangement of the Pu warehouse capable of handling the annual NFC consumption; increase of average burnup for BN-1200 fuel.

Estimate calculations of CFC and liabilities, showed that the first decision, in addition to reduction of processing volumes for the internal NFC, will allow reaching the optimal cost balance in the fuel cycle. The second decision will ensure the plutonium reserve in the system, which will allow solving the problem with BN reactor fuel recourse provision.

Introduction at the foreign market of the services covering the full fuel cycle, including SF processing, allows attracting the additional volume of plutonium from processing to be used in the internal system. Therefore, the warehouse will be formed in the system, which will handle plutonium from processing of Russian and foreign reactors’ SF. Such warehouse filling dynamics must be determined by both internal plutonium consumption within the system reviewed under this scenario, and the stock required in terms of risk minimization. Implementation of this scenario will require to attract by 2100 to the system of 278 tons of plutonium from foreign reactors’ SF, which will in average amount to 200 kg of plutonium per year (11% of fuel load) per each operating BN-1200. The use of foreign SF allows reducing the annual cost fuel component significantly in the NPI system compared to the open NFC (~19%) and the similar scenario for the two-component NPI system (~11%), as this leads to decreased unit costs related to SF processing. As soon as by 2100, the additional plutonium source will allow to form the system, comprising of almost only fast neutron reactors, which will make it possible to stop using natural uranium in the system at all.

The scenario study presented demonstrates that at the given rate of power facilities development (73 GW(el.) by 2100), there are no system restrictions (related to the availability of the resource base) of the BN technology development after 2050. Transition to the two-component NPI system with thermal and fast reactors changes the cost structure and allows reducing fuel costs in the NFC. Changes of exploitation parameters if BN-1200 reactor (BR, external cycle duration, initial and annual fuel load, etc.) allows for controlling flexible the system characteristics (natural uranium consumption, processing volumes, SF and Pu warehouse, etc.), which are critical in view of the NPI system sustainable development arrangement in Russia.

Planned works for increase of average burnup for BN-1200 fuel will decrease expenses in NFC with the insignificant impact on the nuclear materials balances in the system. The possibility of attraction of plutonium extracted from SF of foreign reactors will allow for reducing significantly fuel costs in the NPI, optimizing internal nuclear materials flows, creating the operating reserve of plutonium and attracting around 2.5 thou. tons of foreign SF with the implementation of the service on regenerated plutonium handling within Russian NPI system.

One of priority tasks set by SC Rosatom is launch of the serial industrial fast neutron-based power unit and transition to the closed NFC within the system with thermal and fast reactors. Implementation of the closed NFC will make it possible to improve the VVER NPP export potential by means of a possibility to provide services at the final stage of the nuclear fuel life cycle and to reduce the risk associated with the resource procurement throughout the whole NPP life cycle. Commercial offers for NM processing and handling services are important in the course of development of new markets in emerging countries, since the latter have no technological capabilities to create their own NFC. Here, decisions on the efficient potential use of the uranium and plutonium regenerated materials potential use generated from processing should be elaborated in detail. Making a comprehensive proposal for the fuel cycle organization will make it possible to obtain an advantage at the NPP construction market abroad. The approaches used will allow reducing the final cost of fresh fuel for the customer. Plutonium excreted from SF, may be repeatedly used in nuclear fuel production, but it also serves as a double-purpose product, and its return even in the form of the mixed uranium and plutonium fuel may be associated with certain restrictions.
In this situation, the NPI development strategy in Russia must take into account the possibility of use of the regenerated plutonium energy potential considering internal and external sources. In the long-term perspective, the VVER technology will determine the economic potential of SC Rosatom at the domestic and international markets. VVER reactor fuel component significantly depends on external conditions, in which the reactor is exploited, including the possibility of regeneration materials use in the SF. Calculations show that the CFC for BN-1200 based on the assumptions made may be by 25% lower than that of VVER. This is mainly associated with the achievement of high parameters of average fuel burnup. Further decrease of the CFC for FN-1200 may be associated with the improvement of fuel burnup and reduction of annual load, as well as cheaper fresh fuel production procedures and SF handling. Closure of the nuclear fuel cycle reduces the dependence on changes in the cost of natural uranium and allows making the sustainable system of SF and RW management.

3. Recommendations and objectives for a phased transition to a closed NFC for NFI system of Russia

Based on the results of the estimate and analytical studies of the long-term development, recommendations and tasks of the stage-by-stage transition to the closed NFC for Russian NPI can be elaborated.

The 1st stage is small batch of BN-1200 (3 power units till 2035):
- BN-800 transition to MOX fuel full load;
- obtaining experience of BN-800 MOX fuel processing using the hydrometallurgical method;
- stage-by-stage creation of the VVER-1000/1200 SF processing infrastructure (gradual introduction of processing capacities of ~800 thm/year during the period from 2020 through 2035 taking into account foreign SF processing possibilities);
- creation of industrial MOX fuel production for BN-1200 (with the capacity of no less than 60 thm/year by 2025 with the production expansion possibility);
- putting into operation of the small batch of BN-1200 (from 2027);
- BN-1200 reactors construction and exploitation experience;
- optimization of design and technological solutions for BN-1200 reactors;
- settlement of an issue related to MOX fuel increased burnup;
- making proposals for the SF handling service for foreign customers;
- formation of the required legislative base regulating SF handling and the framework of control over NM non-proliferation in terms of closing NFC;
- resolving the problem with regenerated uranium return in thermal reactors’ NFC;
- estimation of perspectives of plutonium use in thermal reactors (obtaining operation experience);
- generation of the experience of decommissioning of nuclear power facilities;
- resolving technological problems with RW handling (HAW (high-active wastes) deep filling experience).

The 2nd stage is SF, RW and Pu accumulation control (development of the two-component NPI system till 2050):
- BN-1200 technology development based on the experience obtained (serial construction of improved BN-1200);
- closed NFC infrastructure development (industrial production scale, non-aqueous SF processing methods);
- SF and RW accumulation control in the system;
- maximum use of the energy potential of processed SF;
- creation of the two-component NPI system with TR and BN, efficiently consuming regenerated materials (uranium and plutonium);
- increase of the NPI safety level, competitiveness and attractiveness (driving NPI growth rate);
- SF processing business development for foreign customers;
• involvement of the thermal reactor fleet in the closed NFC (Ureg, MOX/REMIX fuel, increased fuel conversion/breeding ratio);
• development of the internal and external market for decommissioning of NRI facilities;
• beginning of exploitation of the 1st and 2nd categories RW final isolation point;
• formation of the perspective NPI image.

The 3rd stage is the guaranteed resource availability:
• expansion of fast neutron reactors construction within the NPI system;
• minimization of natural resources consumption;
• the decision of the question of final isolation issue of RW waste and decommissioning of NPI facilities.

The 4th stage is functioning under the NPI share potential reduction (remote perspective, demonstration of the possibility of scheduled decommissioning of the whole NPI system:
• fuel reproduction is consistent with the power facilities recession rate;
• decommissioning of NPI facilities;
• final guaranteed isolation of all accumulated RW and SF.

4. Conclusion
The study showed the important role of the fast reactor technology in the two-component NPI system, which is determined based on the strategic decisions related to SF handling, long-lived RW and formation of the NPI development strategy aimed at resource availability in the long-term perspective. To make decisions on main development trends and the timeline of the large-scale implementation of the closed NFC technology and introduction of BN reactors to the NPI system, the comparative analysis of material and economic indicators of the NPI development in Russia was carried out for prospective till 2100 involving various scenario variants. An attraction of possibility of additional plutonium generated from foreign SF processing has been reviewed.

Although assessment studies conducted serve as estimates only, they can be used as a good approximation to form the basis for making decisions in the sphere of the NPI development strategy for the next decades.

Based on the scenarios reviewed, the following conclusions can be made:
• non-closure of the NFC within Russian NPI will lead to significant economic and technological risks related to SF accumulation and reduction of the raw materials base;
• the large-scale implementation of fast neutron reactors will require assuring their fuel cycle has flexible parameters (with BR control, duration of the external cycle and fuel loads), required efficiency and safety values;
• main volume of SF at the warehouses till 2035 will include RBMK SF, and it is required to develop the long-term strategy of its processing considering minimization of the impact on the NCF economy (e.g., organization of mutual processing with BN SF);
• there is a significant market share related to foreign NPP SF constructed based on Russian design, which consideration will significantly change requirements to Russian internal NPI system, as well as NFC closure concepts being developed; it is also required to form the balanced proposal for development of the NPI system taking into account the possibilities of thermal and fast neutron reactors;
• small quantity of BN reactors at the stage of transition to the closed NFC prevents from arranging use of large volumes of plutonium excreted from processing. However, at this stage MOX/REMIX fuel use can be initiated in VVER reactors, which are not yet optimized for plutonium use, and such optimization must take place in the future after depletion of available and cheap natural uranium;
• the involvement of plutonium derived from the reprocessing of foreign SF can improve the economic parameters for the domestic fuel cycle.
Putting into operation of BN-1200 reactors in the NPI system with restricted natural uranium reserves prevents from increase of the NPI system capacity to a significant level. If BN-1200 reactors are used it is unnecessary to increase significantly BR in VVER reactors, since their share in this case is very unlikely to exceed one third of the system capacity. In order to increase the thermal reactor share in the NPI system to a significant level by innovations in improvement of the active area of VVER reactor with MMOX/REMIX fuel, quite strict requirements by the NPI system must be established to fast neutron reactors (Super-BN: fuel load (3.5-4) t/GW el., excessive plutonium production - 280-300 kg/GW el. per year). After the task of increase of BR in thermal reactors (Super-VVER) has been solved and using fast Super-BN type reactors mentioned above, a large-scale balanced and multi-product NPI system can be obtained compared to the scenario of the use of the system with BN-1200 reactors only.

Beside the problems with SF and the NFC closure there are new tasks related with establishment of financial relationships among the system components, as well as control by Cash Flows and credits. Assessments of economic efficiency and competitiveness of the current NPP designs should be done taking into account the role, which separate components play in the NFC system. The transition to a new form of relations in the nuclear fuel cycle should be consistent and not cause significant disturbances in the costs of the current period. Estimations and analytical indicators presented in the work demonstrate the problems related to transition to the close NFC with thermal and fast reactors to be operated in the NPI system of the Russian Federation. The studies show as well possibilities of closure of the NFC, which ensures profitable self-provision of the NPI by the secondary nuclear fuel.

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