Closed Nuclear Fuel Cycle

Optimization of Two-Component Nuclear Power System

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Abstract. System study results are presented that demonstrate the feasibility of Russian nuclear power attaining 120 GW(e) level by the century end, taking into account decommissioning of older NPPs that complete their operation life, and assuming the new NPPs commissioning rate of 4-6 power units per 5 years until the year of 2050 and up to 10 units per 5 years in the second half of the century. The possibility of complete nuclear power transition through the stage of two-component structure towards the new technological platform with naturally safe fast neutron reactors domination has been confirmed. No limitations related either to the national uranium resources or to the enrichment capabilities have been revealed.

1. Introduction
With massive increase in NPP generating capacities, the key problem is to ensure an appropriate level of safety and environmental impact of the nuclear power (NP) in general, which will require a higher level of safety of new NPPs compared to that of the existing ones. The solution to this problem is the transition to a two-component NP system with closed nuclear fuel cycle (CNFC) of fast neutron reactors (FR) and thermal reactors (TR).

Scenarios for the introduction of FR with CNFC into NP operating on TR with open NFC should be based on the actual structure of nuclear power system. The ERI-2016 forecast of Russia's power industry development [1] determines the likely scale of growth in electricity production in general and by nuclear power plants in particular until 2040; with its moderate extrapolation to the end of the century with a gradual slowdown the nuclear power contribution by 2100 will be ~500 TWh/year, or ~23% of the total production of ~2270 TWh/year. On the basis of a favorable growth option according to ERI and further extrapolation with more aggressive commissioning of new NPP capacities, the contribution of nuclear power in the optimistic scale of development may be increased to ~850 TWh/year by 2100, or ~31% of the total production of ~2700 TWh/year. Dynamics of electricity generation growth at the two specified scales of development are compared in figure 1.

Figure 1. Electricity generation at the likely and optimistic.
Implementation of the likely scale of development corresponds to the survival strategy of NP, the transition to an optimistic scale of development may be attributed to the safe growth strategy. It is advisable to focus the development of the Strategy-2018 on an optimistic scale of development, providing a “driving prospect” for the industry.

2. Two-Component NP
The central provision of Strategy-2018 is assertion of the need for transition of NP to the New Technological Platform (NTP) with the introduction of FR and closed NFC. In the foreseeable future, the two-component structure of NP should be developed. In this context, two conceptual approaches are being considered: one assumes, at the end of the transitional stage, preservation of a permanent two-component structure with the participation of both TR and FR, the other assumes that this structure may be an intermediate (albeit long enough) stage ultimately leading to dominance of self-sufficient FR, not excluding however the possibility of preserving a limited number of TRs to meet specific requirements of energy production. Assumed dynamics of NPP capacity commissioning by five-year periods for the two approaches are given in table 1.

| Table 1. Dynamics of commissioning/decommissioning of capacities by five-year periods in two approaches to the two-component NP development (a - intermediate, b - permanent). |
|---|---|---|---|---|---|---|
| Years | VVER-1000, 1200, 1250 (GW) | BN-1200 (GW) | BR-1200 (GW) |
| 2021-25 | a | b | a | b | a | b |
| Commissioning | 4.9 | 4.9 | - | - | 0.3 | 0.3 |
| Decommissioning | -4.0* | -4.0* | -0.6 | -0.6 | - | - |
| 2026-30 | Commissioning | 5.0 | 5.0 | 1. | 1. | - | - |
| Decommissioning | -3.0* | -3.0* | - | - | - | - |
| 2031-35 | Commissioning | 4.3 | 4.3 | 1. | 1. | 2.4 | 2.4 |
| Decommissioning | -3.3* | -3.3* | - | - | - | - |
| 2036-40 | Commissioning | 2.5 | 2.5 | - | - | 2.4 | 2.4 |
| Decommissioning | -2.9 | -2.9 | - | - | - | - |
| 2041-45 | Commissioning | - | 2.5 | - | - | 7.3 | 4.9 |
| Decommissioning | -2.0 | -2.0 | - | - | - | - |
| 2046-50 | Commissioning | - | 2.5 | - | - | 7.3 | 4.9 |
| Decommissioning | -3.0 | -3.0 | - | - | - | - |
| 2051-55 | Commissioning | - | 2.5 | - | - | 7.3 | 4.9 |
| Decommissioning | -1.0 | -1.0 | - | - | - | - |
| 2056-60 | Commissioning | - | 2.5 | - | - | 7.3 | 4.9 |
| Decommissioning | - | - | - | - | - | - |
| 2061-65 | Commissioning | - | 2.5 | - | - | 9.8 | 7.3 |
| Decommissioning | -2.0 | -2.0 | - | - | - | - |
| 2066-70 | Commissioning | - | 2.5 | - | - | 9.8 | 7.3 |
| Decommissioning | -1.0 | -1.0 | - | - | - | - |
| 2071-75 | Commissioning | - | 2.5 | - | - | 9.8 | 7.3 |
| Decommissioning | -2.1 | -2.1 | -0.9 | -0.9 | - | - |
| 2076-80 | Commissioning | - | 2.5 | - | - | 12.2 | 9.8 |
| Decommissioning | -5.8 | -5.8 | - | - | - | - |
As a basis for the Strategy-2018 the concept of the intermediate two-component NP structure formation has been adopted as more complete implementation of the new technological platform. A more conservative approach with the permanent two-component NP development should be considered as an alternative option, taking into account the risk of incomplete practical realization by 2030-35 of the expected benefits of the inherently safe FR being developed.

Figure 2 shows the dynamics of commissioning/decommissioning and changes in the structure of the installed capacities of Russian NPPs within the intermediate two-component NP formation stage, and figure 3 gives similar diagrams corresponding to the creation of a permanent two-component structure.

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3. Fuel Balance

The fuel balance of the emerging two-component NP system with NFC closure is determined by the following main factors (in accordance with the operating capacities change dynamics):

- consumption by TR of fresh UOX fuel based on enriched uranium for the launch of new units and further continuous feed in subsequent refueling;
- consumption by FR of fresh UN fuel based on enriched uranium for the launch of new units and their initial feed before the closure of its own nuclear fuel cycle;
- using the TR SNF reprocessing products to produce plutonium-containing starting fuel for FR (mixed nitride uranium-plutonium - MNIT fuel);
- using plutonium from VVER SNF to produce MOX (mixed oxide) or REMIX fuel for VVER with partial closure of their own nuclear fuel cycle;
- use by FR (upon closure of its own NFC) of regenerated MNIT fuel based on plutonium from its own SNF with a breeding ratio of ~1.05 with unlimited recycling;
- use of uranium regenerate from SNF of TR (in priority against the waste uranium) as a feed additive in the manufacture of MNIT fuel for FR, as well as for further enrichment in the production of uranium fuel for FR and VVER.

The influence of these factors, besides the generating capacity growth, depends on the accumulated TR SNF large scale reprocessing start timing related to the expected commissioning of the RT-2 plant (instead of or in addition to the existing RT-1 with a relatively small capacity of ~100 t/year and scheduled start-up of pilot demonstration facility (PDF) for 250 tons/year of VVER SNF). An additional option with a possible implementation in the second half of the century is reprocessing of SNF of RBMK (LWGR), which has a lower plutonium concentration compared to VVER (~0.5%).

The dynamics and structure of fuel consumption in the NP system during NFC closure depend on both the accumulated TR SNF reprocessing products yield and the NPP generating capacities structure changes. In particular, an important factor is the terms of fuel supply and SNF reprocessing for the exported FR. The possibility of on-site NFC facilities export for FR (possibly with some exceptions) has been accepted as the most appropriate solution that meets the requirements of the global nuclear power development, which eliminates the need for cross-border transportation of large amounts of SNF and fresh fuel with significant plutonium content, and reduces plutonium accumulation due to reduction in the duration of the external portion of the nuclear fuel cycle. At the same time, it is assumed that the
FR start fuel export will involve only enriched (up to ~13% U-235) uranium, although the option of the MNIT fuel supply is not excluded.

4. System Research Scenarios

In order to select the baseline scenario for the NP development in Russia that meets the key provisions of Strategy-2018, and taking into account the above considerations, a scenario study has been performed on the basis of RNPE system model (Russian Nuclear Power with Export) built with the programmatic tool USM-1 (System Model Generator) [2]. Nine scenarios were investigated, that ensure the achievement of 120 GW of total installed NPP capacity by the end of the century. The main parameters of these scenarios are given in Table 2.

The first five scenarios differ, all other things being equal, in the start-up time of the RT-2 plant for large-scale reprocessing of VVER SNF from 2030 and up to the time span beyond the considered event horizon (2130). Scenario 6 also provides for reprocessing of RBMK SNF - upon completion of disposal of the accumulated VVER SNF stock. Reprocessing of FR SNF in all cases is timed to the operation of each commissioned commercial power complex (CPC) with on-site NFC assuming 2 years of external fuel cycle duration. Scenarios 7 and 8 suggest the possible fuel balance options:

- with cancellation of the export restriction for the plutonium-containing MNIT start fuel for FR,
- using plutonium from VVER SNF in them themselves in the form of MOX fuel (on a once-through basis).

Scenario 9 illustrates the indicators that can be achieved with a full transition to NTP with FR dominance of by the end of the century, in accordance with the generating capacities structure shown in figure 2.

| No. | Name          | Start-up year of RT-2 | Start of RBMK SNF reprocessing | FR start fuel for export | MOX fuel VVER |
|-----|---------------|------------------------|---------------------------------|--------------------------|---------------|
| 1   | RT2-2030      | 2030                   | -                               | UN                       | -             |
| 2   | RT2-2040      | 2040                   | -                               | UN                       | -             |
| 3   | RT2-2060      | 2060                   | -                               | UN                       | -             |
| 4   | RT2-2080      | 2080                   | -                               | UN                       | -             |
| 5   | Without PT2   | >2130                  | -                               | UN                       | -             |
| 6   | RT2-2060&90   | 2060 2090              | -                               | UN                       | -             |
| 7   | RT2-2060ufea  | 2060                   | -                               | MNIT                     | -             |
| 8   | RT2-2050M     | 2050                   | -                               | UN                       | Yes           |
| 9   | PT2-2040frd   | 2040                   | -                               | UN                       | -             |

a Unlimited fuel export.
b Fast reactor domination.

Comparative assessment of scenarios took into account the following integral indicators of the NP system over the time interval until the end of the century:

- consumption of natural uranium for domestic needs of Russia and for export supplies of nuclear fuel;
- SNF reprocessing volumes and unprocessed residues, including those in the NPPs cooling ponds;
- absolute expenditures, both in Russia and for export;
- investments in NFC facilities, including the medium term ones until 2040;
- system levelized cost of electricity (SLCOE).
According to the results of the study, scenario 9 was recommended as a baseline for Strategy-2018, which envisages a complete transition to NTP with FR dominance by the end of the century. In the scenarios under consideration, the technical and economic data for the open TR NFC stages from known publications were used, and for the closed FR NFC in centralized and on-site options data were obtained from the results of developments within the Proryv Project. The data summary from [3] is given in tables 3 and 4.

**Table 3.** Technical and economic data for NPPs with VVER and CPC with FR (prices of 2016, $1 = 32 rubles).

| Specific capital investments | $/kW(e) | rub/kW(e) |
|-----------------------------|--------|-----------|
| VVER-TOI                    | 3160   | 101000    |
| PEC with RBN-1200           | 2500   | 80000     |

| Operation life               | Years |
|------------------------------|-------|
| VVER-TOI reactor, RBN-1200 reactor | 60    |

| Unit operating costs (without fuel) | $/kW (inst.e) | rub/kW (inst.e) |
|-----------------------------------|--------------|-----------------|
| NPP with VVER-TOI                 | 60           | 1930            |
| PEC with RBN-1200                 | 51           | 1640            |

| Start fuel load                  | t HM         |
|----------------------------------|--------------|
| VVER-TOI reactor (UOX, MOX)      | 77.0         |
| RBN-1200 reactor (MNIT)          | 61.0         |

| Average burnup                   | GW*day/t HM  |
|----------------------------------|--------------|
| VVER reactor (VVER-1000 - VVER-TOI) | 40-60       |
| RBN-1200 reactor                 | 62-115       |

| Fuel life time                   | Effective days (number of refueling) |
|----------------------------------|--------------------------------------|
| VVER reactor (VVER-1000 - VVER-TOI) | 1200-1350 (3) |
| RBN-1200 reactor                 | 1320-2640 (4-8) |

| Annual fueling capacity (with UF =1) | t/year |
|--------------------------------------|--------|
| VVER reactor (VVER-1000 - VVER-TOI) | 27.4-20.6 |
| RBN-1200 reactor                    | 16.5-8.9 |
Table 4. Technical and Economic Data for NFC (prices of 2016, $1 = 32 rubles).

| On-site NFC within CPC with FR | Unit | Value | Unit | Value |
|-------------------------------|------|-------|------|-------|
| Specific capital investment in CPC on-site NFC | M$/ (t/year) | 44 | Million rubles/ (t/year) | 1400 |
| SNF reprocessing + MNIT fuel refabricaion in CPC | M$/t | 6.4 | Million rub/t | 207 |
| Storage of U-Pu regenerate from FR SNF | M$/t/ year | 0.15 | Million rub/t/ year | 4.8 |
| Storage of HLW (burnup of 7-12%) | M$/t | 0.06 – 0.11 | Million rub/t | 1.9 – 3.4 |
| HLW (burnup of 7-12%) final disposal | M$/t | 0.044 – 0.082 | Million rub/t | 1.4 – 2.6 |

**Centralized NFC of FR**

| Specific capital costs, plant for fresh MNIT fuel (40 t/year modules) | M$/ (t/year) | 22.5 | Million rubles/ (t/year) | 720 |
| Fabrication of MNIT fuel | M$/t | 4.0 | Million rub/t | 128 |
| Fabrication of fresh UN fuel for FR ~60 t/year at the existing plant | M$/t | 1.75 | Million rub/t | 56 |

**Centralized NFC of VVER**

| Original cost of natural uranium | $/kg | 100 | rub/kg | 3200 |
| Cost of separative work: | $/SWU | 110 | rub/SWU | 3520 |
| - natural uranium, | | | | |
| - regenerate from VVER SNF | | 121 | | 3872 |
| Spec. capital costs, fresh UOX fuel plant, ~1000 t/year | M$/ (t/year) | 1.9 | Million rubles/ (t/year) | 61 |
| Spec. capital costs, VVER SNF reprocessing plant, (~700 tons/year) | M$/ (t/year) | 2.6 | Million rubles/ (t/year) | 82 |
| Fabrication of UOX fuel for VVER, ~1000 t/year | M$/t | 0.37 | Million rub/t | 11.8 |
| Fabrication of MOX fuel for VVER, 250 t/year | M$/t | 2.14 | Million rub/t | 68.5 |
| Reprocessing of VVER SNF, 1000 t/year | M$/t | 0.60 | Million rub/t | 19.2 |
| Plutonium storage in storage facilities | M$/t/ year | 1.1 | Million rub/t/ year | 35 |
| Spec. capital costs, SNF storage facilities: wet 6000 t | M$/t of capacity | 0.065 | Million rub/ton of reservoir | 2.1 |
| dry 9000 t | | 0.048 | | 1.5 |
| Away-from-reactor storage of SNF | M$/t/ year | 0.008 | Million rub/t/ year | 0.26 |

5. Reprocessing of TR SNF

Figure 4 shows an example of the dynamics of accumulation and reprocessing of TR SNF with allowance for both domestic and foreign (from exported NPPs) deliveries and taking into account the operation of RT-1 (until 2035) and PDF (from 2025 to 2060). In this ex-ample, the RT-2 plant with 700-
800 tons/year capacity is commissioned in 2040. The capacity of the 500 tons/year module for reprocessing of foreign SNF is taken into account separately. By the middle of the century, the maximum accumulation of VVER SNF is close to 10,000 tons, the accumulated volume of RBMK SNF after completion of their decommissioning will be ~26,000 tons.

Upon completion of disposal of the VVER SNF accumulated volumes, the reprocessing rate will be adjusted by varying the UF against the delivery rate of new SNF. In the case of an intermediate two-component structure (figure 3a), disposal of accumulated SNF stock will be completed 10 years earlier than in permanent structure, even at a slightly lower capacity of the RT-2 reprocessing plant, which may later be used to reprocess RBMK SNF (figure 3c), and then at the end of its service life will be decommissioned as unnecessary. In the case of a permanent two-component structure (figure 3b), reprocessing of VVER SNF should continue in a stationary mode even after 2100.

![Figure 4. Reprocessing of RT spent nuclear fuel in a two-component NP.](image)

### 6. Dynamics of Total Fuel Consumption

The dynamics of fuel consumption of Russian NPPs with its constituents for baseline Scenario 9 is shown in figure 5, including supplies of fuel for exported NPPs (but excluding recycled fuel from exported FR produced in on-site nuclear fuel cycle abroad). In a system with an intermediate two-component structure (figure 5a), with the growth of NPP capacity by 2100 up to 120 GW(e), the total fuel consumption by the end of the century will remain close to the current level due to the efficiency of FR replacing VVER. To maintain the continued growth of the FR fleet at the end of the century, under conditions of plutonium supply cessation from VVER SNF, up to 12-15% of the FR fuel consumption may be covered by marginal uranium fuel.

The total fuel consumption in a system with a permanent two-component structure (figure 5b) almost doubles by the end of the century due to the need to provide fuel for ~30 GW(e) VVER fleet which use it almost twice less efficiently compared to FR (evolutonal growth of average burnup for VVER is expected from 4.3% in 2010 to 6.2% by 2030, and for FR - from 6.5% in 2030 to 12% by 2050). This also takes into account the saving of fuel supplies for FR abroad, which, when their NFC is closed, become self-sufficient (require make-up only from virtually unlimited resources of waste uranium).
a) intermediate (Scenario 9)  
b) permanent (Scenario 2)  
c) permanent with VVER MOX (Scenario 8)

Figure 5. Fuel consumption of Russian NPPs in a two-component NP system, including export.

In scenario 2 with a permanent two-component structure of NP, given the scale of NP development in Russia and the ratio of VVER and FR capacity of 1:3 achieved by the end of the century, the given increase in FR capacity is entirely covered by plutonium resources from VVER SNF (including return from exported, plus from own recovery with breeding rate of ~1.05), so that an additional external source of FR fuel in the form of enriched uranium is not required (figure 5b). The latter is used only for the start fuelling and initial make-ups before the closure of NFCs of exported FR. Moreover, in Russia, under these conditions, an excess of U-Pu regenerate is left for the production of FR MNIT fuel (see figure 6 below), which essentially could be used for export deliveries instead of uranium fuel. This would save uranium resources and improve the economy of the nuclear fuel cycle. But given the uncertainty in terms of the risk of plutonium-containing fuel supplies abroad from the point of view of non-proliferation policies, this scenario remains an alternative.

The dynamics and structure of fuel consumption when using MOX fuel for VVER are shown in figure 5c (Scenario 8). In this scenario, the available plutonium stock is used to manufacture MOX fuel for VVER, the “secondary” plutonium from MOX SNF (unsuitable for recycling in VVER) is applied to produce fuel for FR, and “improved” plutonium from FR SNF is used for new MOX fuel of VVER.

When using MOX fuel, the VVER fuel consumption increases slightly due to the limitation of the burnup (50 GW*day/t versus 60 GW*day/t for UOX) associated with the degradation of isotopic composition during recycling. For FR, the transition to the use of Pu from MOX SNF of VVER reduces the fuel resource due to deterioration of Pu quality after irradiation in VVER: Pu concentration in the start fuel must be 22% higher. Compensation for this effect requires the use of the marginal uranium fuel, which reduces the savings in natural uranium consumption achieved for VVER. The benefit of uranium saving with the use of MOX fuel for VVER is fully true only within the framework of a single-component NP employing TRs, whereas in the transition process of creating a two-component structure of NP this option has a negative effect. This statement also applies to the concept of saving uranium using REMIX-fuel for VVER. The crucial point is that it is more profitable to use all available fuel resources in FR rather than in the TRs. This thesis is confirmed by further comparison of the key integral indicators of the considered scenarios.

7. Nuclear Materials Stock Changes

The dynamics of changes in NM stock for the production of nuclear FR fuel is shown in figure 6. The stock of warehouse plutonium for 2010 is estimated at 104 tons, including ~45 tons of civil-grade plutonium and ~50 tons of ex-weapon grade plutonium in terms of the equivalent to the civil-grade one with a coefficient of 1.18 obtained from the neutron-physical calculations of the Proryv ITC. In all scenarios this stock, taking into account the continuing supplies from RT-1 and, possibly, from PDF, is supposed to be spent for the production of start-up “fresh” MNIT FR fuel by 2050-55. The dynamics of the use of the uranium regenerate stock from VVER SNF for each scenario is calculated individually.
based on the condition of a smooth operation of the separation facility engaged in the regenerate re-enrichment.

a) intermediate (Scenario 9)  
b) permanent (Scenario 6)  
c) permanent with export of MNIT fuel (Scenario 7)

**Figure 6.** Stocks of NFC products for production of FR fuel in the two-component NP system in Russia.

The U-Pu regenerate stock (without separating plutonium from uranium) for MNIT FR fuel is being accumulated, on the one hand, as a result of VVER SNF reprocessing at the RT 2 plant according to the schedule adopted for this scenario, and on the other hand, from reprocessing of FR own SNF in the on-site NFC of each CPC in accordance with the adopted 2 years duration of the external fuel cycle. Taking this into account and considering the dynamics of changes in the ratio of VVER and FR capacities (figures 2, 3), an excess of U-Pu re-generate may accumulate in the NFC system. In the case of the permanent two-component system, by the end of the century this excess will reach ~1,300 tons even with a late start-up of RT-2 in 2060 (figure 6b), which corresponds, in terms of heavy metal, to the same amount of fuel after fabrication, and further continues to grow. This suggests that the system in question, which maintains a given capacity of VVER, over-consumes natural uranium, eventually turning it into unrequired fuel. This excess may be partially reduced if we cancel the restriction on the use of MNIT fuel for the starting of exported FR, as can be seen from figure 6c. A radical solution to this problem is achieved in Scenario 9 with a transition to the dominance of FR (figure 6a), which ensures the most efficient use of all fuel resources.

**8. Requirements for natural uranium and separation work**

The dynamics of uranium consumption in the two-component NP is shown in figure 7.

a) intermediate (Scenario 9)  
b) permanent (Scenario 6)  

**Figure 7.** Dynamics of uranium consumption in the two-component NP.
Current consumption of uranium for domestic needs of Russia from 2020 to 2040 is slightly reduced due to the slowdown of VVER commissioning (see, figures 2, 3), and then continues to decrease due to the use of stock (figure 6) and new uranium regenerate from VVER SNF for re-enrichment. Savings due to re-enrichment of the uranium regenerate in figure 7 is shown as a negative component of uranium resource consumption (lower curve) taking into account the difference in the U-235 content ~1.3% versus 0.7%.

In the case of a complete transition to the NTP in scenario 9 (figure 7a), on the one hand, as mentioned earlier, at the end of the century the supply of uranium regenerate from VVER SNF for re-enrichment decreases to complete cessation, and to continue the commissioning of FR (figure 5a) there is a need for uranium, but on the other hand, the decommissioning of VVER reactors gives a much greater saving of uranium consumption by the nuclear power system as a whole (cf. figure 7b), and there is a clear tendency to completely eliminate this need (except for the export component, the need of which is still open).

The dynamics of the integral consumption growth for the two compared scenarios is given in figure 8, which also shows the dynamics of the separation work requirements in the form of two constituents - for all NPPs in Russia and for all exported ones. Saving in the separation work due to re-enrichment of uranium regenerate from VVER SNF (taking into account the difference in U-235 content ~1.3% versus 0.7% in natural uranium) is attributed to domestic consumption, therefore the requirement of the separation work for Russia is lower at equal fuel consumption with exported NPPs.

Scenario 9 (figure 8a) shows that the complete transition to the NTP, despite the above-mentioned need for uranium to continue FR commissioning at the end of the century, allows saving ~40 kt (~10%) of natural uranium in domestic consumption by 2100. This confirms the idea that the best way to save uranium is its primary use in FR. It is also can be seen that the curve of integral domestic consumption in scenario 9 levels off signaling the possibility of stopping uranium mining and enrichment, whereas in scenario 6 it continues to grow, and this is an unsolved problem of NP with a permanent two-component structure.

As can be seen from figure 8, export deliveries of uranium fuel at the adopted scale of NPPs export increase the need for natural uranium by about half, which requires special consideration in terms of policies for the use of national resources. At the same time, it can be noted that in all the compared scenarios, the requirements for the enrichment capacity (including work for export) throughout the considered time interval until the end of the century and beyond do not exceed the existing level of ~20 MSWU/year.
9. Nuclear Fuel Production Dynamics of Total Fuel Consumption

The production of nuclear fuel for Russian and exported VVER NPPs in baseline Scenario 9 is shown in figure 9a in terms of the required volumes and the corresponding installed capacities. Similar diagrams for the production of uranium start fuel for the domestic and exported FR are shown in figure 9b. Commissioning of new capacities are related to the growth of needs, the operation life of facilities is assumed to be 50-60 years.

[Diagram a) VVER fuel b) VVER fuel]

Figure 9. Uranium fuel production (baseline Scenario 9).

The parameters of centralized production of "fresh" MNIT fuel for FR based on plutonium from VVER SNF are shown in figure 10a, and regenerated from the own FR SNF in the on-site nuclear fuel cycle - in figure 10b. Figure 10a shows the contribution of production both with the use of separated plutonium from the stock and with the new technology being developed, from the U Pu regenerare.

[Diagram a) centralized (Pu from VVER SNF) b) On-site NFC in Russia (Pu from FR SNF)]

Figure 10. Production of FR MNIT fuel (Scenario 6).

10. Cost of Nuclear Fuel

The cost of nuclear fuel under conditions of NFC closure should be determined taking into account the principle of compensation for the costs of waste management resulting from its use by consumers of this fuel, i.e. NPPs. Thus, the cost of new uranium VVER fuel includes the costs of spent fuel reprocessing, intermediate storage and final disposal of the generated radioactive waste. Accordingly,
reprocessing products in the form of plutonium, uranium regenerate or U-Pu regenerate are considered free for the production of new fuel, for example, MOX for VVER or MNIT for FR. The cost of MOX fuel for VVER includes the cost of its reprocessing, but not the primary reprocessing of UOX SNF. Similarly, the cost of reprocessed FR fuel from its own SNF includes the cost of its reprocessing and treatment of radioactive waste. Specific cost indicators for calculating the above costs are given in table 4 above.

The cost of uranium of various enrichment grade, including natural one, is shown in figure 11. Cost estimate of natural uranium is based on the data of 2001 White Paper of NP in Russia [4], wherefrom the cost profile (in relative units) versus various resources categories in kilotons has been obtained using linear interpolation (figure 11a). The dynamics of expected actual growth of the natural uranium cost over time (right scale in figure 11b) is determined taking into account the integral consumption for each specific scenario. A single normalizing factor is also used to allow binding data to current values adopted worldwide and in the industry to-day. In this study, the value of this factor was taken so as to give the initial value of natural uranium of $100/kg, as indicated in table 4.

The cost of enriched uranium for VVER fuel shown in figure 11b takes into account the use of uranium regenerate from VVER SNF for re-enrichment as discussed above, so that from mid-century to 2100 this cost is reduced despite the continuous increase in the natural uranium cost. The latter factor is fully manifested in the growth of the cost of uranium fuel for the start fuel of exported FR while the use of the regenerate re-enrichment is reserved for the needs of the nuclear fuel cycle in the country.

![a) extraction cost profile](image1.png) ![b) cost dynamics over time (Scenario 9)](image2.png)

**Figure 11.** Cost of natural and enriched uranium.

The dynamics of changes in the cost of enriched uranium determines, respectively, the cost of UOX fuel as shown in figure 12a for baseline Scenario 9. Figure 12b shows a similar diagram for MOX fuel from Scenario 8.
The UOX fuel cost jump at the end of the century is due to uranium regenerate supply reduction for re-enrichment upon completion of accumulated VVER SNF disposal (see figure 4), then the cost increase follows the natural uranium cost rise. The cost of MOX fuel (figure 12b) is mainly conditioned by the cost of manufacture, which is almost 6 times higher than the cost of manufacturing UOX fuel (see table 4 and cf. figure 12a). The increased values of this cost in the middle and at the end of the century are due to lower utilization of production capacities at the initial stage of their commissioning and subsequent upgrade upon the expiration of their operation life. The assignments for MOX SNF reprocessing and radioactive waste treatment are identical to those for UOX fuel in figure 12a, but in this case there are no cost for obtaining the primary nuclear product - plutonium, which is included in the costs of UOX SNF reprocessing. (Similarly, plutonium obtained during the reprocessing of MOX SNF is considered free of charge for the production of MNIT fuel for FR).

Dynamics of MNIT fuel cost structure are shown in figure 13.

The cost of fuel from third-party plutonium (figure 13a), i.e. coming from storage and VVER SNF reprocessing, as mentioned above, does not include the cost of obtaining this plutonium as the source NM. The costs for the reprocessing of spent nuclear fuel generated from this fuel are not added either,
since they are included in the cost of the reprocessed fuel. Variations in the cost of production until the middle of the century reflect changes in the UF of centralized production facilities, but with achieving the steady-state mode of operation this cost becomes 1.6 times less than that of the on-site reprocessed fuel production at individual CPCs (figure 13b). In the latter case, the cost of own FR SNF reprocessing makes a significant contribution comparable to the cost of manufacture. The unit costs for HLW treatment from 1 kg of fuel in both cases are assumed identical and slightly increase until the middle of century, thus reflecting the assumed evolutionary increase of the fuel burnup, as mentioned above when discussing fuel consumption.

For side-by-side comparison, figure 14 shows a selection of the cost values of various NPP fuels from diagrams in figures 12, 13. In particular, it is shown here that if the costs of VVER SNF reprocessing are charged to Pu consumers, then the cost of plutonium-containing MOX fuel for VVER and MNIT fuel for FR becomes obviously unacceptable. The need to pay for plutonium from SNF of TRs is sometimes explained by a market approach. However, in a very market-advanced country like the United States, the use of plutonium in FR is considered as a service for its disposal, which requires an appropriate payment [5], then the plutonium cost contributions in figure 14 would have to be negative.

**Figure 14.** Cost structure of various types of nuclear fuel.

11. **Fuel Share in the Cost of Electricity Cost of Nuclear Fuel**

The fuel share in the cost of electricity (FSCOE) is determined by the considered cost values of various fuel types and the fuel consumption structure as well (see figure 5). Figure 15 shows the dynamics and structure of FSCOE separately for the TR fleet and FR fleet.
The TR fleet FSCOE is slightly reduced by 2030 due to the envisaged increase in the average burnup of VVER fuel to 60 GWe*day/t, as well as a reduction in the production of SNF with the decommissioning of RBMK reactors and a corresponding decrease in the SNF reprocessing assignments. With the beginning of large-scale VVER SNF reprocessing at RT-2 plant in 2040, contributions to FSCOE from natural uranium and its enrichment are significantly reduced due to significant input of uranium regenerate for re-enrichment. Upon completion by 2085 of the accumulated VVER SNF stocks disposal, that input is reduced, and FSCOE begins to grow under the influence of higher natural uranium prices and an increase in enrichment costs.

The FR fleet by 2030 uses MNIT fuel (see fuel consumption structure in figure 5a) from a centralized plant, and FSCOE is relatively high due to the increased cost of its manufacture at the first stage of operation, as noted above (see figure 13a). When centralized production reaches its design UF, the cost of this fuel decreases, but the contribution of more expensive reprocessed fuel into FSCOE becomes larger (see figure 5a and figure 13b), and later its cost dynamics determine the behavior of FSCOE which remains almost constant at a level of 6 c/kWh to the end of the century and beyond.

12. Overall System Costs and Electricity Costs Fuel Share in the Cost of Electricity

Figure 16a shows the dynamics and structure of investments in integrated NFC of two-component nuclear power system (including investments in on-site NFC facilities abroad). The structure of investments incorporates 4 constituents:

- centralized fuel production for VVER and FR, including export;
- on-site NFC facilities of CPC with FR in Russia;
- similar facilities abroad;
- centralized plant for TR SNF reprocessing, including SNF returned from exported NPPs.

The time reference of investments in the above facilities corresponds to the fuel consumption dynamics in figure 5a and SNF reprocessing in figure 4 taking into account the replacement of facilities with expired operation life (see also figures 9 and 10).
a) NFC investment structure

b) System current and levelized cost of electricity (SLCOE)

Figure 16. System expenses and electricity costs (baseline Scenario 9).

The summary diagram in figure 16b shows the dynamics of the overall system costs, taking into account all NPP generating capacities and NFC facilities, including exported ones, but with the exception of investments into enrichment plants, since in all the considered scenarios the requirements for separation work do not exceed the level of existing capacities. The cost of enrichment was determined using the unit cost of the separation work listed in table 4 on the assumption that it includes the cost of renovation.

From this figure it is clear that, in general, investments in nuclear fuel cycle account for only about 10% of investments in NPP generating capacity. Thus, the reduction of specific capital investments in the construction of power units with FR is of key importance for the competitiveness of two-component NP.

The current system cost of electricity (taking into account all system costs) is significantly reduced from 5.8 to 3.6 c/kWh by the end of the century as the FR fraction in generating capacity increases. Its levelized value (SLCOE), also shown in the figure, is determined at a discount rate of 5%, which corresponds to an adequate consideration of future costs impact over a fairly long time interval. By analogy with the cost of electricity, the levelized system FSCOE has been determined (taking into account the total fuel costs in a closed NFC), its value does not exceed 20% of SLCOE.

13. Selection of the Baseline Scenario according to Integral Indicators

According to integral consumption of uranium (figure 17), the least efficient are Scenario 5 (without RT-2 commissioning) and Scenario 4 (with RT-2 commissioning delayed until 2080). In both cases, the required integral of uranium consumption, taking into account the production of fuel for export, significantly exceeds national resources indicated by a restrictive red stripe (the left border at ~ 730 kt corresponds to own national stocks, and the width of the stripe accounts for additional foreign assets).
The main reason for the increased uranium consumption in scenarios 4 and 5 is the need to use additional uranium start fuel for the growing fleet of FR after 2070, in the absence of plutonium supply from RT-2. This problem does not manifest itself with an earlier launch of RT-2 - from 2030 to 2060, and the corresponding scenarios (1-3, 6) are equivalent in this regard. Scenario 6 should, in principle, provide some additional savings of uranium due to the reprocessing of RBMK SNF, but since it does not begin before 2090, this gain is manifested outside the scheduled time interval of up to 2100. Allowance for export of MNIT start fuel for exported FR without changing the domestic needs of Russia significantly reduces the consumption of uranium resources to ensure export fuel supplies for only VVER (cf. scenarios 3 and 7). The use of VVER MOX fuel (Scenario 8), taking into account the above-mentioned deterioration of the FR fuel balance (see figure 5), results in the integral uranium consumption saving of about 25 kilotons (up to 6%), but in the baseline Scenarios 9 with the transition to FR dominance the saving may be 40 kt, and without complicating the NFC system with the development of MOX.

Integral volumes of SNF reprocessing and its accumulation (figure 18) do not change upon commissioning of RT-2 before 2060 (scenarios 1-3). In scenarios 4, 5 with a later launch and the same plant capacity, the completion of accumulated VVER SNF disposal goes beyond the horizon of 2100, and the integral amount of reprocessing decreases, while the accumulated amount of non-reprocessed SNF increases. When the RBMK SNF reprocessing (Scenario 6) is commissioned by the end of the century, the ratio of reprocessed and non-reprocessed SNF somewhat improves, but scenario 9 is most effective in this regard due to a decrease in the contribution of VVER to SNF accumulation and the short duration of the external fuel cycle of FR.

**Figure 17.** Integral consumption of natural uranium by 2100.
Figure 18. Integral reprocessing of SNF by 2100.

Figure 19 compares some of the considered scenarios for integral investments in the development of closed nuclear fuel cycle in Russia. Given the urgency of the problem of investment resources in the near and medium term, data are presented until 2040. With a delay of RT-2 plant start-up from 2030 to 2060 (scenarios 1 and 3), savings of $4 billion can be obtained, the same gain is achieved in scenario 6 which provides for the start of RBMK SNF re-processing at the end of the century. Compared to the latter the baseline scenario 9 leading to FR dominance, requires $2.6 billion more.

Figure 19. Integral investments in NFC until 2040.

Figure 20. System levelized cost of electricity (SLCOE) in the time interval up to 2100.
Figure 20 gives a comparison of the same scenarios in terms of the system levelized cost of electricity, SLCOE. The discount rate of 5% has been used for calculating SLCOE to the horizon of 2100, which gives an adequate long-term estimate.

The calculation results show the preference for delayed launch of RT-2 up to 2060. A significant increase in SLCOE occurs only when it is shifted to 2080 and beyond. Some gain (less than 1%) with the launch of RT-2 in 2030 (scenario 1) compared with the later versions can hardly be justified due to the need for increased investment in the nuclear fuel cycle in the period up to 2040 (figure 19). Scenario 9 with the achievement of FR dominance, despite the need to increase investment in nuclear fuel cycle as noted above, will provide SLCOE no worse than in comparable scenarios 2, 3, 6, while providing the above-mentioned advantages in terms of fuel resources saving and SNF reprocessing.

14. Conclusion
The overall results of the system study demonstrate the possibility of the Russian NP reaching the level of 120 GW(e) by the end of the century, taking into account the decommissioning of NPPs with expired operation life, at commissioning rate of 4–6 units per 5 years before 2050 and up to 10 units per 5 years in the second half of the century. The feasibility of two-component NP structure creation before the end of the century with VVER and FR operating in an integrated closed NFC has been confirmed as well as the complete transition of NP through the two-component structure stage to NTP with dominance of FR with inherent safety. There are no restrictions either on the national resource base of natural uranium or on the capacity of the enrichment facilities. A scenario with the key indicators as shown in table 5 could be recommended as a baseline one for Strategy-2018.

Table 5. Key Indicators for the recommended baseline scenario.

| Key Indicators                                                                 | By 2050 | By 2100 |
|--------------------------------------------------------------------------------|---------|---------|
| Installed capacity of nuclear power plants in Russia, GW                        | 52      | 120     |
| including VVER                                                                  | 29      | 0       |
| including FR                                                                    | 23      | 120     |
| Installed capacity of exported NPPs, GW                                          | 30      | 88      |
| including VVER                                                                  | 18      | 10      |
| including FR                                                                    | 12      | 78      |
| RT-2 commissioning, VVER SNF reprocessing, first stage, tons/year               | 500     |         |
| Additional capacity for SNF of exported VVER                                    | 500     |         |
| Second stage of RT-2                                                            | 250     |         |
| Reprocessing of RBMK SNF (since 2090)                                          |         | 150-750 |
| Capacity of on-site NFC of FR (reprocessing/refabrication), tons/year            | 190     | 900     |
| Integral consumption of uranium, kt                                             |         | 725     |
| including for Russia                                                            |         | 375     |
| Integral investments in NFC, billion dollars                                    |         | 11.8    |

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