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THE INITIAL STAGE OF CLOSING THE NFC OF THE RUSSIAN TWO-COMPONENT NUCLEAR POWER ENGINEERING SYSTEM

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The study proposes a stepwise scheme of the initial stage in the transition to a closed nuclear fuel cycle (NFC) two-component nuclear power engineering system comprising fast and thermal reactors. The closure of the NFC appears to be economically justified due to the envisaged construction of between six and nine BN-1200M fast neutron power units. Since no scarcity of plutonium is expected by 2031, the assumed year of commissioning the BN-1200M fast neutron reactor, it is expedient to defer the processing of spent plutonium fuel and instead store it into the middle of 2050s, reducing capital and fuel costs. However, it will be cost-effective to begin full-scale processing at centralized productions after 2050, since the expected quantity of spent fuel from fast reactors will by then be sufficient to achieve significant reductions in the specific cost of its processing.

The transition of Russian nuclear power engineering over the next decades into the mode of a two-component nuclear power system with thermal and fast reactors in accordance with the development strategy is one of the basic goals of the Rosatom State Corporation [1, 2]. At present, objective technological uncertainties, vagueness in the development rates of the domestic economy, and different approaches to the closure of the nuclear fuel cycle (NFC) preserve possibilities for the various scenarios of achieving this goal. Thus, the aim is established to close the fuel cycle inside a small group of identical fast reactors using the infrastructure of industrial-energy complex in the mode of the fuel self-provision and repeated recycling of irradiated nuclear fuel with a maximally short holding time [3]. The conditions of interaction between reactors within one such complex with a centralized or near-station fuel supply require a special consideration. An alternative approach proposes to realize the fuel supply of fast reactors with single-use plutonium from the spent nuclear fuel of thermal reactors, as well as to defer the processing of this spent fuel – i.e., in essence, to implement the plutonium-open fuel cycle at the initial stage [4]. Other proposals are also advanced.

Under these conditions, the planning and implementation involved in the initial stage of the NFC closure represent the most complex and critical moment in the selection of the strategy for closing the NFC not only for individual reactors, but for the nuclear power engineering system as a whole.

Thus, the present work assesses the technical and economic advantages of the deferred processing of the spent nuclear fuel of fast reactors in comparison with the option of the immediate recycling of plutonium from it.

Model scenario for the development of the Russian nuclear power engineering. The selection of the most effective option of the initial stage in closing the NFC is based on the technical and economic analysis of commissioning sodium fast reactors. The option of the accelerated introduction of BR-1200 reactors with a lead coolant is not examined due to the absence of information about its design characteristics.

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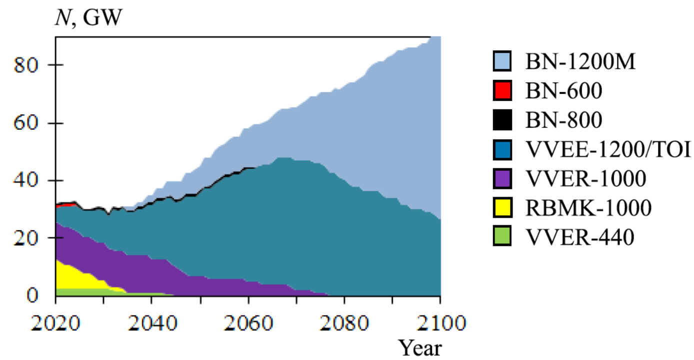

Fig. 1. Capacity structure according to the scenario of VVER + fast reactors using uranium oxide and mixed uranium-plutonium fuel, respectively.

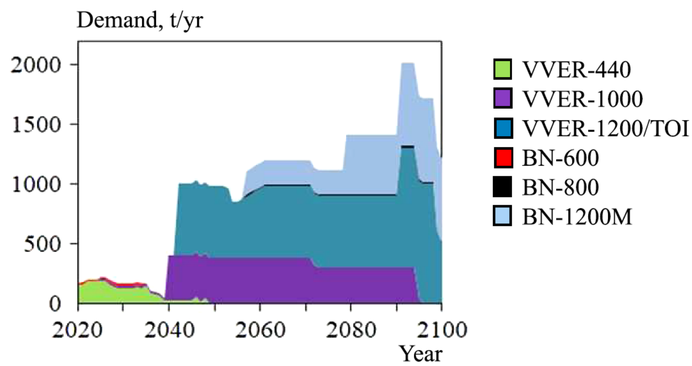

Fig. 2. Pattern of demands in processing the spent fuel for the plutonium supply of BN-800 and BN-1200M.

The study was conducted using the CYCLE code comprising the mathematical modeling of the nuclear power fuel cycle [5]. The scenario is based on water-water energetic reactor (VVER) and fast reactor technologies, as well as on the fuel cycles, tested in the operation. In accordance with the accepted scenario, Figure 1 demonstrates the structure of the installed capacities in the Russian nuclear power engineering up to 2100, which is close to the basic scenario presented in [2]. This scenario assumes that a BN-1200M (fast neutron reactor) head power unit will be commissioned in 2035 using mixed uranium-plutonium fuel with an average discharge burnup of up to ~13%. Then, until 2055, it is planned to commission a small series (eight power units) of BN-1200M fast commercial reactors having a breeding interlayer of depleted uranium. In order to ensure the installed capacities, the basic option of the strategy [2] implies the commissioning of VVER thermal reactors using uranium fuel to be continued until 2070. After 2070, the growth of installed capacities will be ensured by the commissioning of only BN-1200M fast reactors. VVER-1200/TOI (universal optimized digital pressurized water reactor) reactors can be operated until their design life ends by about 2130.

Despite new-generation VVERs even now being projected to utilize both uranium oxide and uranium-plutonium fuel, this option is not considered under the present scenario due to the uncertainty in the time of involving the mixed uranium-plutonium fuel in the NFC. In addition, options of BN-1200 fast reactor without the breeding interlayer and using nitride fuel were not considered. With the exception of the RBMK-1000 (high-power channel-type reactor), it is assumed that that the spent fuel of thermal reactors is processed and the plutonium used for preparing the fuel for BN-800 and BN-1200M.

The processing capacity and annual efficiency of processing the spent fuel of thermal reactors are selected under the condition that the reserves of the stored isolated plutonium do not exceed ~100 t. Figure 2 illustrates the pattern of demands in spent fuel processing capacities for thermal and fast reactors, which are necessary to provide plutonium for BN-800 and BN-1200M reactors for the period up to 2100. In addition, this figure demonstrates that the need for processing the spent fuel of fast reactors with regard to the shortage of plutonium will appear after 2055.

Figure 3 shows the dynamics of stored plutonium reserves, taking into account its supply for the production of mixed uranium-plutonium fuel for fast reactors. Here, the amount of plutonium isolated as of January 1, 2021 was assumed to be

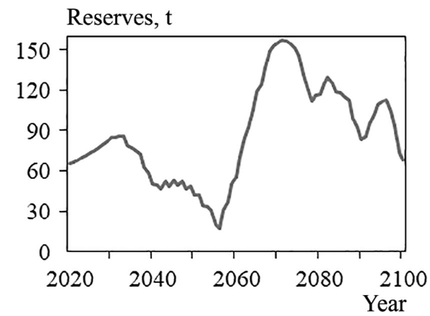

Fig. 3. Dynamics of stored plutonium reserves at the end of the year.

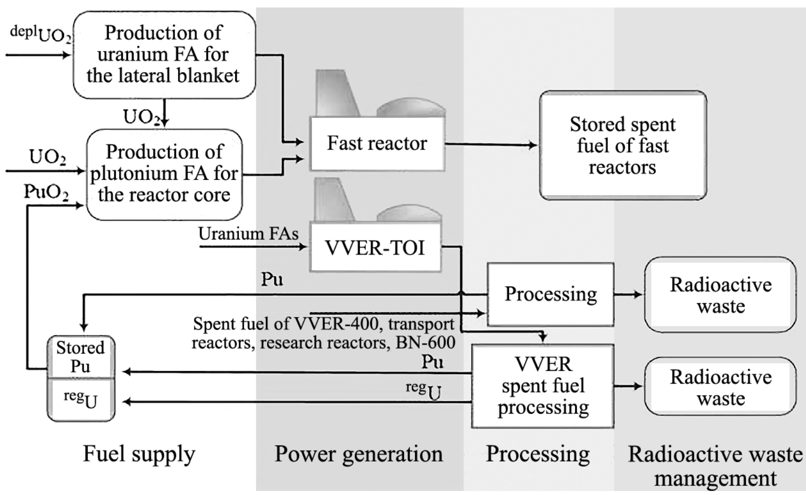

Fig. 4. Structure of the closed NFC at the initial stage of the transition to a two-component nuclear power system.

~60 t [6]. It is evident that the reserves of plutonium reach the minimum of ~20 t up until the middle 2050s, which is connected with the exhaustion of the main volume of the spent fuel of thermal reactors; however, it is still sufficient to continue the commissioning of several additional BN-1200M reactors. Obviously, this time can be interpreted as the completion of both the initial stage in closing the NFC of nuclear power engineering and the solution to the problem of accumulated VVER spent fuel, as well as the start of processing the spent fuel of fast reactors.

According to the expected structure of the nuclear fuel cycle during the initial stage in the transition to a closed NFC shown in Fig. 4, fast reactors actually operate in the open plutonium fuel cycle during this period.

According to the estimation of the present state of stored plutonium reserves, as well as plutonium projected to have accumulated in the spent fuel of thermal reactors by 2035, its quantity is sufficient for commissioning the BN-1200M head power unit and continuing its operation till the end of the 60-yr design resource period. Moreover, the quantity of plutonium is enough to launch several additional standard fast reactors. Thus, using the mixed uranium-plutonium fuel, no scarcity of plutonium for fast reactors is anticipated at least until the middle of the century.

Fast reactors can be used to significantly improve the isotopic composition of plutonium loaded into them, especially taking into account the ^{239}Pu accumulated in the breeding blanket [7]. This property allows this plutonium to be reused in thermal reactors even after its single use in the composition of mixed fuel for pressurized water reactors (PWRs) [8].

The extraction of plutonium from the lateral breeding blanket at a rate of ~100 kg/yr is characterized by its comparatively low content of the breeding material, which can influence the economic expediency of its processing. Therefore, in the absence of a plutonium scarcity or requirements to adjust its isotopic composition, it is possible to temporarily abandon the lateral breeding blanket. In this case, fuel costs for its production and processing are excluded and it can be substituted by a cheaper steel screen. The present study considers both options, i.e., a lateral blanket and a steel screen.

The question arises whether it is economically feasible to operate a BN-1200M in the open plutonium cycle with deferred spent fuel processing as compared to the option of the constant recycling of the spent fuel with a short holding time.

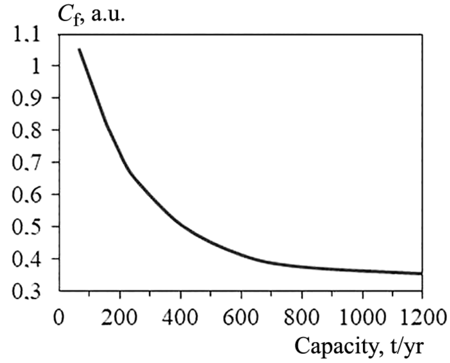

Fig. 5. Unit cost of the spent fuel processing versus plant capacity.

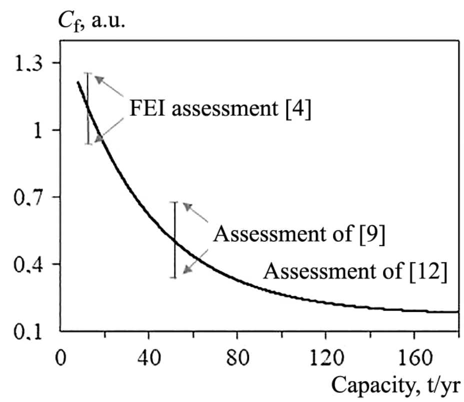

Fig. 6. Unit cost of producing FAs with mixed uranium-plutonium fuel versus plant capacity.

Let us consider the cost indicators for the main technological stages of a closed NFC, including the spent fuel processing and production of fresh fuel, as well as their dependence on the capacity of corresponding industries. Although the indicated technological stages make the greatest contribution to the NPP fuel costs, the real unit costs of NFC technological stages are subject to commercial confidentiality of fuel recyclers and producers, as well as the purchasers of these services. Therefore, known cost indicators typically represent expert estimates obtained according to the indirect evidence. In this connection, the cost indicators will be further considered in relative units.

Processing the spent fuel of fast reactors. The main reason why deferred processing may be more feasible consists in the exclusion of high unit capital costs for the construction of small-tonnage – and, consequently, less cost-effective – fuel processing and production facilities. This can lead to a noticeable reduction in NPP annual fuel costs and the fuel cost component, leading to a lower total cost of electric power production.

Foreign data of [9, 10] were used along with estimations of the Zababakhin All-Russian Research Institute of Technical Physics (VNIITF) specialists to plot the qualitative dependence of the specific cost of processing the spent fuel of thermal reactors on the efficiency of a plant (Fig. 5). In this case, uranium oxide fuel is processed using a water-extraction processing technology based on the PUREX process. A transition to mixed uranium-plutonium fuel using identical utilized technology and plant capacity increases the cost of spent fuel processing by ~10% [11].

According to the data of the study [9], which refers to the long experience of commercial enterprises including French ones on the processing of LWR spent fuel, the capacity of ~1000 t heavy metal/year is economically optimal and agrees well with the data of Fig. 5.

Producing the mixed uranium-plutonium fuel of fast reactors. Taking the processing cost into account, the unit cost of producing FA with mixed uranium-plutonium fuel obviously depends on the scale of the nuclear fuel production. An indication of this dependence is given by the study [12], whose results are presented in Fig. 6. In this case, the significant corridor of uncertainties estimated in [9] and by the Leipunskii Institute for Physics and Power Engineering (SSC IPPE) [4] is encountered. These results indicate that economically acceptable fuel costs for the production of FAs with mixed

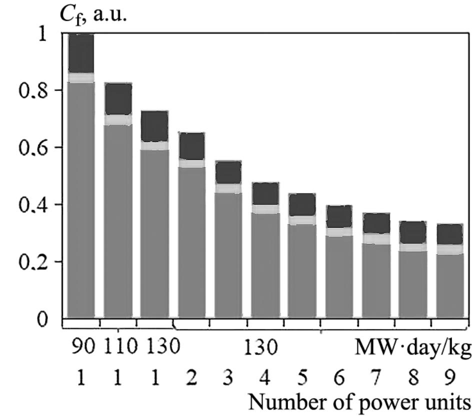

Fig. 7. Dependence of the fuel component in the BN-1200M electric power production cost on the average burnup and the number of units in the system: (■) total, (■) without processing, (■) without spent fuel processing and exclusion of the lateral blanket.

uranium-plutonium fuel begin with between six and nine BN-1200M power units. In this case, the annual demand is around 70–100 tons of heavy metals.

To obtain a more accurate assessment of the significance of fast reactors in a two-component nuclear power system, it is necessary to consider the two-product nature of a fast reactor production, i.e., the production of electric power and accumulation of plutonium for the entire nuclear power system, for example, in accordance with the proposals of [13].

Evaluating the technical and economic efficiency of the proposed measures at the initial stage of closing the NFC. The reduction of investment costs for the creation of commercial units to process the spent fuel of fast reactors will be not less than $300–400 million (~25 billion rubles) for 2021. [14]. Deferred processing leads to the need for supplying fast reactors with the plutonium of the VVER spent fuel. In this case, the stored spent fuel of thermal reactors will be intensively consumed; spent fuel of fast reactors can be stored following appropriate modernization of premises.

The initial stage of fuel cycle closure takes a relatively short period of time equal to 20–25 years as compared to the full nuclear fuel life cycle of ~100 years. Therefore, in order to isolate technical and economic indicators, including the fuel cost component of this particular stage, they must be considered through the annual fuel costs. Otherwise, upon their consideration through the reduced fuel costs, which are typically related to the entire life cycle, the influence of the initial stage will be substantially distributed over this 100-yr period. The following model was adopted to calculate fuel costs:

– the head power unit with a BN-1200M reactor is operated sequentially in three modes of an average fuel burnup equal to 90, 110, and 130 MW·day/kg of heavy metals;

– then, a small series of eight power units with BN-1200M reactors is to be commissioned. All power units of this series are operated at an average burnup of 130 MW·day/kg;

– synchronously, taking into account the two-year period for the production of initial loadings in accordance with demand, the facilities producing fresh and processing spent fuel are commissioned;

– unit prices for the production of FAs with mixed uranium-plutonium fuel and processing in terms of a plant capacity function are modeled in the form of continuous dependencies (see Figs. 5, 6);

– unit prices of all remaining NFC technological stages are accepted as constant. The relative insignificance of errors in fuel costs due to this assumption follows from their contribution to annual fuel costs.

Figure 7 shows the diagrammed relative fuel cost component for three cases: total, taking into account the processing of the spent fuel of fast reactors and lateral blanket; taking into account the lateral blanket, but with deferred spent fuel processing; taking into account the deferred spent fuel processing and a steel screen.

Along with an increase in average burnup and the number of BN-1200M power units, deferred processing leads to a 20–30% reduction in the fuel cost component. Due to the scale factor at the stages of producing mixed uranium-plutonium fuel and spent fuel processing, the fuel cost component reduces almost two-fold when the number of commissioned power units is increased to 9. The efficiency of replacing the lateral blanket with a steel screen is significantly less, ranging from 3% to 10%.

Recommendations for reducing fuel costs at the initial stage of transition to a two-component nuclear power system. Based on the obtained results, the following gradual scheme of the initial stage in closing the NFC can be proposed:

– commissioning of the BN-1200M head power unit and its operation with an average burnup of 90 MW·day/kg of heavy metals in combination with a low-capacity production of 10–15 t/yr for the manufacture of FAs with mixed uranium-plutonium fuel;

– sequential transition of the head power unit during the development of appropriate technologies to operation at an average burnup of 110 and 130 MW·day/kg of heavy metals;

– commissioning of a small series of BN-1200M as a part of eight power units with an increase in fuel production capacity to ~60 t/yr;

– maintaining the operation of nine power units without processing until the exhaustion of the spent fuel plutonium and storing of the spent fuel of fast reactors with the deferred processing, at least, until ~2055;

– commissioning of a specialized facility for processing the spent fuel of fast reactors with a capacity of at least 200 t of heavy metals/year, marking the end of the initial stage in closing the NFC.

Conclusion. Under the conditions of the absence of plutonium scarcity, the authors propose to begin the transition to a two-component nuclear power system with the deferred processing of the spent uranium-plutonium fuel of fast reactors until the period after 2050. The immediate processing of this spent fuel appears to be inadvisable for the economic reasons due to its insignificant quantity. In the absence of natural uranium and plutonium scarcity, the temporary exclusion of the lateral blanket becomes economically feasible.

The construction of between six and nine power units with BN-1200M reactors can be justified for the initial stage of closing the NFC. Due to the scale factor, the construction of a single power unit would result in higher fuel costs per unit of produced electric power.

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