Justification and optimization of FNR transition to the closed fuel cycle mode

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Abstract. The «Proryv» project implies developing advanced nuclear technologies for next generation large-scale nuclear power based on fast neutron reactors (FRs) operating in a closed nuclear fuel cycle (NFC). All components of the closed NFC must be in agreement with the requirements for the product characteristics and optimized in accordance with the different stages of the fuel cycle. Different variants of the closed nuclear fuel cycle are being looked into with different types of FRs, fuel, and fuel cycle facility arrangement options (centralized or on-site). Many processes and technical solutions, which are being used to develop the fuel recycling technology, have never been applied on a commercial or laboratory scale. Successfully implementing this technology implies developing a system of codes within the «Proryv» project, which would allow researchers to model various closed NFC options using a hierarchical approach. Dedicated computer software is used for optimizing particular closed NFC modules (the reactor, fuel fabrication and reprocessing modules). Optimization criteria are selected based on the requirements for characteristics of the products (in relation to quality or production time), which are in turn obtained from calculating the system as a whole. The functional possibility of conducting correlated calculations for FR cores and back-end nuclear fuel cycle processes was developed, which enabled researchers to factor in the effect of variable reactor core arrangement, startup fuel characteristics, equilibrium state attainment strategies and SNF composition on technology components and closed nuclear fuel cycle management.

1. Introduction
The Proryv project covers the development of the complex nuclear technology of the future large-scale power industry of the new type based on the use of fast neutron reactors operating within the closed nuclear fuel cycle [1-2]. Under the Proryv Project, the development of fast neutron nuclear facilities with the mixed nitride uranium-plutonium fuel within the closed nuclear fuel cycle has been carried out.

Since characteristics of a reactor facility have the controlling influence on the requirements set up to the closed nuclear fuel cycle (CNFC) technologies and the operation arrangement, the possibility of related calculations for FR cores and closing process stage of the CNFC must be provided for. This is necessary for taking into account potential variations of the core arrangement, initial loads, strategies of transition to the equilibrium mode and of the SNF composition on operation of technologies components and CNFC organization.

Complex organization of the fast reactor fuel cycle, continuous alternation of the refabricated fuel delivered for the core load within much more continuous time period (compared to existing reactors operating within the open fuel cycle), almost completely eliminate so-called mean steady-state modes
(prior to transition to the equilibrium mode). The model should provide for automated and quick calculation of the core fuel life cycle for the time period of at least 20-30 years, taking into account overloads and fuel recycles.

Therefore, one of key tasks in designing and operation of the nuclear facility is simulation of the nuclear facility life cycle taking into account overloads based on the actual fuel composition. Here, various CFNC variants depending on FNR types, fuel types, station or centralized location of closed nuclear fuel cycle process stages must be reviewed. Many processes and technical solutions used to implement selected fuel recycling technologies have not been previously applied in the industry or trial use.

2. RTM-2 Software System

RTM-2 Software System (SS), which has been developed under the "Proryv" project direction since 2013, is designed to optimize the core overloads based on the actual fuel composition and taking into account closing fuel cycle process stages. The model provides for automated and quick calculation of the core fuel life cycle for the time period of at least 20-30 years, taking into account overloads and fuel recycles, which is vital for correct analysis.

RTM-2 SS has the possibility of settlement of the following tasks:

- automated detailed calculation of time characteristics of fuel consumption and reproduction for all intervals between refueling at three main stages: initial fuel load and partial fuel feed prior to the recycle start, the transition period up to reaching the equilibrium mode, equilibrium mode operation;
- detailed calculation of the fuel nuclide (isotopic) composition and analysis of its influence on the reactor facility operation parameters;
- carrying out multi-variant calculations to assess the impact of general technological solutions on the nuclear fuel cycle closure at the stage of PDEC and IEC design and implementation to facilitate making best decisions.

These tasks can be resolved by means of combining in one software complex of two components: the first component (RTM-NF) performs simulation of the nuclear facility, and the second (RTM-FC) performs simulation of nuclear fuel cycle process stages.

The detailed description of functions of each part of the software system is presented below.

RTM-NF controls units, which perform neutron and physical calculation of the FN’s core and of isotopic composition evolution. Any diffusion calculation code can be integrated in the SS as the unit performing the neutron and physical calculation. The calculation results are neutron and physical characteristics of the core and the fuel isotopic composition for each FA. Based on neutron and physical characteristics, the RTM-2 SS user evaluates of the estimated characteristics meet the TR and NSR requirements.

RTM-FC, in its turn, performs simulation of the nuclear fuel cycle process stages. The following fuel cycle process stages are simulated:

- spent fuel pool, this component (unit) of program estimates the isotopic composition evolution during ageing of spent FA;
- the processing unit separates isotopic compositions of spent FA in processing products and RW. At this time, all RW components are removed from the calculation and their content is not subject to further control;
- raw materials and processing products warehouse. This component (unit) performs control over the processing products from the processing unit and takes into account their consumption by the fabrication unit. Two warehouse variants are available: external raw materials source used to form the initial load and to feed till recycle application, and the processing products warehouse. The warehouse of raw materials and processing products is also used in calculation of time characteristics of fuel components production/ consumption;
- fabrication unit is also aimed at formation of new FA at the RTM-NF request.
Automated interaction is established between RTM-NF and RTM-FC. RTM-NF provides RTM-FC with spent FA isotopic compositions, as well as places an order for manufacturing new FA. RTM-FC, in its turn, returns to RTM-NF isotopic compositions of fresh FA obtained in the fabrication unit.

Fresh FA isotopic composition is determined as a result of performance the selection algorithm. The selection algorithm performs the search of such fuel composition, which criticality would be equal to the value set up by the user at the given precision degree. The search of the fuel component is carried out by means of variation of plutonium share. The chart of data exchange in the isotopic composition selection process is given in figure 1.

Figure 1. The chart of estimate data exchange between RTM-NF and the FC external part calculation unit in isotopic composition selection.

RTM-FC includes two independent software units, each of which may be used for simulation the fuel cycle external part. The first unit considers the fuel cycle technologies used. Its analytical model is a simplified analytical model made in VIZART SS [3-5]. The second analytical model is the Ideal Fuel Cycle Model. This model is not related to the fuel cycle closing stage technologies. This model idealization implies having the properties, which can be freely varied by the user: fuel cycle duration and chemical elements transition tp the processing products. This model objective is assessment of fuel balances and characteristics of the NF core at simultaneous variation of the material flows content at fuel cycle process stages. This model can be useful to solve a wide range of study tasks, in which no detailed presentation of the FC external part is required.

RTM-2 also performs the following functions:
- presentation of the graphic interface for designing the reactor model, calculation scenario (the scenario includes the number of intervals between refueling, their duration, overload interval duration, overload maps) and fuel cycle external part parameters setting.
- visualization of initial data and calculation results;
- comparing calculation results;
- processing of calculation results (search for highest reached values of the core characteristics, integration of values by space and time, averaging) and formation of excel reports.

The software system’s capabilities are expanded by adding of software units, which perform the additional NF analysis based on the calculation results obtained. The additional analysis may be represented with, e.g. assessment of coefficients and effects of CPS WO reactivity and balances at various stages of the NF operation, up to reaching the equilibrium mode of operation.
3. Nuclear facility life cycle calculation results
One of new technology’s key tasks is to ensure such fuel composition and such characteristics of the
core with new fuel and minimum reactivity runout throughout the NF’s whole life cycle starting with
the reactor power start-up. This must lead to reduction or exclusion of the risk of reactivity accidents
with severe consequences. Main problem with the calculations involved not only the need in evening
out fuel compositions at overloads in the process of transition to the equilibrium mode of the nuclear
facility, but also simulation of the overload system with establishment and replacement of constant
reactivity compensators at the initial stage of operation. To solve the task set, the RTM-2 software
system was used. Results of the detailed simulation of the NF’s whole life cycle are given in the
example of the nuclear facility with the lead coolant and combined nitride uranium plutonium
(MNUP) fuel taking into account fuel overload. The wide range of plutonium: from low-background
to the basic with long plutonium ageing time period and low content of Pu-241. was reviewed as basic
isotopic compositions.

The fast reactor core with the heat capacity of 700 MW with the lead coolant consists of 169
hexagonal cells. The central part of the core consists of 109 hexagonal cells, including:
- 86 CC (central core) FA cells;
- 7 FA cells with core working objects (core WO);
- 4 FA cells with AP (automatic control pin) (working objects (AP WO);
- 12 FA cells with SP (shim pin) working objects (SP WO);

The peripheral part of the core consists of 60 hexagonal cells of the FA PR (peripheral part): The
core chart is given at figure 2.

**Figure 2.** Core and side reflector chart (1 – central part FA, 2 – peripheral part FA, 3 – central part FA
with core WO, 4 – central part FA with SP WO, 6 – reflector block, 7 – protection unit, 8 – reflector
block with the signal receipt and processing device (SRPD), 11 – central part FA with AP WO).

The chart of uniform partial FA reload in transition to the steady-state mode of operation and the
operating in this state, characterized with an equal number of FA quantity re-loaded to one reload and
the equal duration of the interval between reloads. Main characteristics of the FA core reload model
are given in Table 1.
Table 1. Basic variant main characteristics.

| Characteristics                        | Value  |
|----------------------------------------|--------|
| Capacity, MW                           | 700    |
| FA number, pcs                         | 169    |
| Duration of the interval between refueling, eff. per day: | 330    |
| Reload model                           | uniform partial (see figure 4) |
| Number of cycles, pcs.                 | 5      |
| Stop between reloads (refueling), eff. per day | 30     |
| Number of FA renewed per reload, pcs.  | 34     |
| External fuel cycle duration, years    | 2      |
| Number of start-up intervals between refueling, during which own fuel is not used. | 3      |
| Established recourse (accepted in calculations), years | 60     |

Table 1 contains the mean number of core FA renewed per one reload. Taking into account actual FA distribution by reload groups (see figure 3), the number of FA being reloaded will amount to 33-34 pcs based on the operation interval. These calculations use the interval duration between reloads of 300 eff. per days.

Figure 3. Uniform partial reload mode (N – reload number; R – reload frequency).

3.1. Description of fuel scenarios under review
The following reactor fuel is used on scenarios reviewed in studies:

- MNUP based on the isotopic plutonium composition used in BREST-OD-300 Project (BREST).
- MNUP based on the warehouse low-background plutonium (low-background) with waste uranium added (0.1% U-235);
MNUP based on the warehouse energy plutonium of VVER reactors with small ageing period and increased content of Pu-241 ~9 %; (“9.3 %”, Pu isotopic composition without MA corresponds to the composition further marked as VVER;)

As it will be discussed below, Pu-241 plays an important role in reactivity behavior at burnup (the closer to the equilibrium concentration around 3-4%, the better). The highest (maximum) content of Pu-241 used is 9.3 %, the minimal - in low-background plutonium with the content of around 1%. Involvement of MA in fuel is not only efficient in terms of their trans-mutation, but also in terms of minimization of the reactivity reserve. Therefore, for all isotopic compositions variants with minor actinides (MA) added to the fuel load based on the following simple logics were reviewed. If heat reactor SNF serves as the plutonium source for the fast reactor start-up, then after its processing it is feasible to use not only plutonium, but also other actinides in the proportion they are contained in SNF. Np and Am maximum shares with respect to plutonium equals to around 8.5%, 17% in aggregate, i.e. up to 2.2% with respect to all fuel for heavy atoms. The ageing period will have an impact on Pu-241 and Am-241 shares, with their amount preserved. At the process stage, the MA share in VVER SNF may reach 25% relatively Pu. As to the fast reactor fuel, taking into account the enrichment (of Pu mass share) of around 13-14%, the MA share in the fuel may reach 3%.

Start-up loads have increased BRC, which in a number of cases results in the reactivity growth during burnup and increased highest reactivity reserve level. Physically this is associated to the fact that start-up loads have no absorption and, therefore, the neutron balance in the fresh core is better than in the burnt-out core. To overcome this effect, it is suggested to add at the initial stage to the core the adsorbing agent instead of a part of fuel, which will serve as constant (unlike movable CPS shafts) reactivity compensator and imitate absorption at fission fragments.

3.2. Calculation results
Curves of the reactivity change for initial variants are presented at figure 4. The use of low-background plutonium lead to the necessity of the largest reactivity reserve (0.4 % ΔK/K). Like with low-background plutonium, large reactivity volume is required to use plutonium with the relatively fresh isotopic composition with great content of Pu-241 (around 9 w.%). It should be noted that reviewed compositions allow for ensuring the required reactivity reserve almost at the whole life cycle. In all estimated variants, the maximum reactivity reserve was around ~0.4 % ΔK/K. In the equilibrium state operation mode, excessive reactivity is present and amounts to ~0.1 % ΔK/K.

![Figure 4. Reactivity change curve for initial variants.](image-url)
Minor actinides play the role of an additional burning-put absorber, and their share may serve as an additional reactivity reserve improvement factor (figure 5).

Figure 5. Reactivity change core with the addition of minor actinides to the start-up load.

Figure 5 shows that irrespectively of the number of minor actinide addition, excessive reactivity for the start load was observed in variants. To compensate for excessive reactivity, constant reactivity compensators (CRC) were installed in the start-up core. Borocarbon containing B-10 and dysprosium titanate were used as an adsorbing agent in CRC. Results are given at figure 6.

Figure 6. Reactivity change curve with the minor actinides added and CRC installation.

FA replacement with constant reactivity compensators lead to alternation of FA capacity and, thus, of the fuel component linear load. As an example, results of the calculation of distribution of the capacity in the the FA core and the highest fuel component linear load for the baseline variant and the variant with installation of 6 borium CRC in the core at the beginning of the interval are presented (figures 7-8).
Figure 7. Distribution of FA capacity in the start-up load at the beginning of the interval, MW (left - Baseline variant, right - Installation of 6 borium CRC).

The maximum FA capacity in the central subzone with 6 CRC installed increased from 5.90 to 6.72 MW, for FA in the peripheral sub-zone by 4.36 MW and 5.55 MW correspondingly. The maximum FA linear load in the central subzone increased to 470 W/cm, FA in the peripheral subzone to –444 W/cm. Compared to the initial variant, the maximum linear load value increased by ≈12.4%.

Figure 8. Maximum linear load on the fuel component at the beginning of the interval, W/cm with 6 borium CRC installed (left - Baseline variant, right - Installation of 6 borium CRC).

The results of calculations given above show that reactivity stabilizes relatively quickly with the time period corresponding to the fuel-element lifetime. Plutonium composition itself during the first interval changes relatively quickly, and then goes to the full equilibrium during a significantly long period. First several irradiation cycles are the most critical in terms of assurance of the necessary reactivity reserve. Therefore, we suggest separating the equilibrium state concept, which, first of all, should imply the state by reactivity and asymptomatic equilibrium state, which is characterized with the similar composition of plutonium loaded in and loaded out and, therefore, its reactivity and the reactivity of all fuel. figures 9–10 shows relative deviations of plutonium and minor actinides (Np, Am) isotopes from the equilibrium value through out the whole life cycle for various start-up
compositions. The equilibrium isotopic composition meant the isotopic composition of plutonium for the basic variant at the time interval of 60 years.

![Figure 9](image9.png)

**Figure 9.** Relative deviation from Pu equilibrium content for various start-up loads during the lifecycle.

![Figure 10](image10.png)

**Figure 10.** Relative deviation from MA equilibrium content for various start-up loads during the lifecycle.

4. Conclusion

The series of calculation studies performed showed the possibility of use of various plutonium fuel types with the equilibrium core properties preserved. “Various plutonium fuel types” implied the use in the start-up load of a wide range of isotopic compositions of plutonium: from low-background plutonium to basic plutonium with relative ageing and low Pu-241 content.

“Equilibrium core” and “equilibrium fuel” concepts may be distinguished. Equilibrium core means the active area, in which reactivity changes during the fuel-element lifetime and fuel burnup do not exceed $\beta_{\text{eff}}$. Equilibrium fuel means the fuel composition content, formed in the course of multiple recycling after the fuel processing within the equilibrium core ($\sim 30$ years).

The task of reactors of natural safety is the operation in the equilibrium state by reactivity from the start-up load till full achievement of the equilibrium state, i.e. throughout the whole NF life cycle. The time of transition to the equilibrium core if, therefore, absent (equals to zero).

Irrespective of plutonium isotopic composition at the start-up load, it is possible to ensure core operation in the reactivity equilibrium state by adding certain amount of minor actinides. Here, the maximum MA concentration in the fast reactor fuel was determined with MA and Pu ratio in the spent nuclear fuel of the heat reactor, so that all trans-plutonium elements were involved in the fuel cycle following the processing. This should be combined with the use of constant reactivity compensators during first intervals between refueling (1 to 3), which prevent from unfavorable reactivity growth associated with the fuel reproduction excess in start-up loads due to temporary absence of fission fragments.

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