The scheme for evaluation of isotopic composition of fast reactor core in closed nuclear fuel cycle

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Abstract. The PRORYV (i.e. «Breakthrough» in Russian) project is currently under development. Within the framework of this project, fast reactors BN-1200 and BREST-OD-300 should be built to, inter alia, demonstrate possibility of the closed nuclear fuel cycle technologies with plutonium as a main source of power. Russia has a large inventory of plutonium which was accumulated in the result of reprocessing of spent fuel of thermal power reactors and conversion of nuclear weapons. This kind of plutonium will be used for development of initial fuel assemblies for fast reactors. To solve the closed nuclear fuel modeling tasks REPRORYV code was developed. It simulates the mass flow for nuclides in the closed fuel cycle. This paper presents the results of modeling of a closed nuclear fuel cycle, nuclide flows considering the influence of the uncertainty on the outcome of neutron-physical characteristics of the reactor.

1. Introduction

The code REPROYV (REcycle for PRORYV), which simulates the process of loading, processing, and handling of fuel assemblies in the cores of BN-600, BN-800, BN-1200 [1, 2, 3] and other advanced fast reactors was developed to support the PRORYV project. The code can be used to analyze closed nuclear fuel cycles. It allows to study the possibility of the self-sufficient mode of operation in fast reactor. Similar work on the modeling of neutron-physical characteristics of the stationary states of the reactor core with detailed scheme of refueling of fuel assemblies was performed for the BN-600 reactor and was presented in [4]. A third-party software tool is used to calculate fuel radiation and depletion on each step of fuel burnup. We can use these data to analyze external fuel cycle stages. Any product can be used as the third-party code, which meets the requirements to get the needed functionality.

Russian code JARFR [5] is applied at present in the REPROYV. The code is designed for evaluation of neutron-physical characteristics of fast reactors in the multi-group diffusion approximation [6]. It released with application constant support based on the library of nuclear data, BNAB 93.01 [7]. JARFR can model the entire active core with separate fuel assemblies. This program enables to set various properties of different fuel assemblies in the core of the considered reactor.
Thus, the program JARFR allows to take into account the history of irradiation of fuel assemblies, their unique isotopic composition at any given point of time.

We study the influence of isotopic composition uncertainties to the final result (multiplication factor, the amount of plutonium in the reactor) in 60 years of work on the power. Fuel is (Pu-U-N).

Special input file of JARFR code is required for correct operation of REPRORYV code. Results are calculated by using JARFR code on each step based on this input file. To analyze the closed nuclear fuel cycle it is needed to specify some input parameters in REPRORYV input file: cooling time, reprocessing time, fuel reload layout, distribution of isotopes into different groups, and conditions of processing for each of the groups.

Fuel reload layout indicates an order in which fuel assemblies need to be unloaded (Figure 1). The user can specify the part of the core which is unloaded each year. Detailed example of fuel reload layout is considered below.

![Fuel reload layout (60 degrees symmetry sector).](image)

It is important to separate isotopes correctly to the groups and then operate with groups of isotopes on the stages of reprocessing. User may choose one of three options for each group as follows:

- Do not change a group concentrations, i.e. retain the mass of group as it was unloaded;
- Remove the group after recycling (assign concentrations to zero);
- Assign the initial value of the mass of the group, i.e. add or remove mass of the group so that the mass would be the same as at the first loading. When this option is selected, concentrations of each isotope can be changed while the whole mass should be the same as at the initial step.

Thus, the user can allocate separate groups of plutonium isotopes (to change mass to its original value, "removing the excess of plutonium"), uranium (to add mass to the initial level by adding $^{238}$U), structure materials (to leave them as they were) and actinides (remove them from reprocessed fuel, or leave them in case of the post-combustion scenario).

Various reload layouts may be entered to agree with stated designers specifications. The effect of plutonium losses on fuel reprocessing stages is studied. Little loss of plutonium is allowable under equipment pollution in processes of separation of fuel fractions and fission products. To specify the input data of REPRORYV, the data from publications on the isotopic composition of fuel, energy release in the core composition and structural materials [8] were used in this work.
2. Uncertainties and errors of calculations

Advantage of the code REPRORYV is the possibility of direct calculation of the errors in the concentrations on the basis of errors in the input data. For this purpose, third-party code of nuclide kinetics BPSD (Burning and Poison calculation System with Deviation) [9] is used in REPRORYV code. The BPSD code was developed in the Institute of the Problems of the Development of Nuclear Power of the Russian Academy of Sciences (IBRAE RAS). This code allows to calculate any chains of nuclide transitions both for actinides and fission products. Library RUSFOND (IP PE) simulating up to about 1500 fission products and up to 40 actinides is used as database for BPSD code. Feature of the program is the direct calculation of the above-described errors: errors of the used numerical methods and errors of the input data, which are set inside the program. The result containing numerical values of the errors allows the user to take into account in their work the possible inaccuracies associated with the simulation, to get the confidence interval, the maximum deviation value, etc.

The user of the BPSD code has to assign the input data for the beginning of every step of burnup that is shown in figure 2. These input data are:

- Concentrations of actinides.
- Multi-group (26 groups) cross sections of fission, radioactive capture, \((n,2n)\) and \((n,3n)\) reactions.
- Neutrons spectrum (26 groups).

![Figure 2. Simplified scheme of the BPSD program with the output of errors of the concentrations.](image)

This module allows turn on function of estimation of uncertainties of the mass for any time of reactor operation into the REPRORYV code. These uncertainties allow estimate the error of the resulting functionals, such as reactivity and density effects of reactivity. In this paper the effect of uncertainty on the final result of the simulation is considered.

3. Processing

Simulation of the recycling process in the REPRORYV code is based on the assumption that the output spent fuel should consist of two fractions: the product and the waste. Scheme of processing in REPRORYV code taking into account uncertainties in isotopic composition is shown in figure 3.
In general case, the schema of processing is nonlinear and depends on many factors. Some of the software codes specifically designed to simulate the process of fuel reprocessing, separation of individual sections of processing lines, calculation of the processing coefficients relying on the chemical reactions, refining, etc. In the REPRORYV code, all processing steps are replaced by one common stage, after which it is already clear what part of the isotopes is the product and what part of the isotopes is waste. The general scheme of closed nuclear fuel cycle simulated in the task by the code REPRORYV is shown in figure 4.

This simplified scheme allows us to specify vector of coefficients of processing for each isotope, removing the complexity of the scheme of spent fuel reprocessing. After processing the waste is directed to the burial, and the product is used to create new fuel loading for the reactor. Vector of coefficients of the separation of the product from the waste for the major isotopes (~20-30 isotopes) is assigned as the parameters of the separation process. Values of these coefficients of the separation were obtained with account of losses and errors. The following equations are used at each step of processing to obtain the new concentration values:

- \( \tilde{\rho}_{\text{product}} = \tilde{k}_{\text{rect}} \times \tilde{\rho}_{\text{in}}; \)
- \( \tilde{\rho}_{\text{waste}} = \tilde{k}_{\text{waste}} \times \tilde{\rho}_{\text{in}}; \)
- \( \tilde{k}_{\text{rect}} + \tilde{k}_{\text{waste}} + \tilde{d} = 1; \)
- \( \tilde{k}_{\text{rect}} > 0; \tilde{k}_{\text{waste}} > 0; \tilde{d} > 0. \)
Where $\vec{\rho}_{inn}$ is vector of concentrations of isotopes at the beginning of the procedure of processing;

$\vec{\rho}_{product}$ is vector of concentrations of isotopes in the product after processing;

$\vec{\rho}_{waste}$ is vector of concentrations of isotopes in the waste after processing;

$\vec{k}_{rec}$ is vector of coefficients of processing. Each component of this vector contains coefficients of processing for each of the major isotopes. Coefficient of processing means the share of the transition of each isotope in the product;

$\vec{k}_{waste}$ is vector of the coefficients of the transition to waste. Each component of this vector contains coefficients of transition to the waste for each of the major isotopes. Coefficient of transition to waste means the share of the transition of each isotope into the waste;

$\vec{d}$ is vector of the share of losses in the processing specified by the user.

It is obvious that each element of these vectors is greater than zero, and the sum of these vectors is equal to a unit vector (the law of conservation of mass).

There are certain difficulties in obtaining accurate values of losses at each operation of the processing. However, assignment of approximate values dives a possibility for the application of the algorithm with accurate data, which can be obtained experimentally directly in the processing plant.

After starting the program with all assigned required characteristics of the fresh fuel, irradiation parameters, cooling time, etc., the output file will contain the isotopic composition of the fuel for loading into a new reactor, its mass, neutron-physical characteristics of all active core and its parts, the errors of the obtained values.

The general scheme of operation of the program REPRORYV is presented in figure 5.
4. Core reloading layout

Reloading layout of the fuel assemblies in the BN reactor core was accepted as follows. It was assumed that plutonium content was 12.8%. Plutonium isotopic composition corresponded to that of discharged from the spent nuclear fuel of VVER-440 reactors [10]. Initially new fuel assemblies were loaded in the core. In the first step of reloading after 330 days of operation, 12 fuel assemblies of 72 (1/6 part of the core) marked by index of "1" (first lot of fuel) in Figure 1 were unloaded and placed into intrareactor storage for cooling until the activity of these fuel assemblies would decrease to the level when they could be reprocessed. This time of cooling was evaluated as two years in our case. New fuel assemblies with the original composition were placed to the positions of unloaded fuel assemblies during following 35 days. The time of operation during 330 days and time for reloading of 35 days were assumed for all steps of reloading. The total time was equal to one year. In the second step of reloading after next 330 days of operation, fuel assemblies marked by index of "2" (second lot of fuel) were unloaded for cooling and replaced by new fuel assemblies during 35 days. Then reactor operated again during 330 days and so on. After two years of cooling, fuel assemblies of type "1" that have been loaded first, were sent for recycling. Several variants of reprocessing were considered. Actinides are removed from the fuel. In the process of separation of fission products, a little amount of plutonium could be extracted along with fission products. The amounts of plutonium as impurity to separated fission products of 0.1% were considered. The time of reprocessing was assumed as one year. In the third step of reloading the fresh fuel assemblies were place to position "3" and the reactor operated for following 330 days. Finally in the fourth step of reloading, recycled fuel which was reprocessed over the last year was placed to position "4" (on the contrary to the fresh fuel as in the previous steps), composed of the first lot of fuel. Then, in following steps of reloading, fuel assemblies that have been unloaded and reprocessed after the second step (second lot) would be placed in position "5", after the third step - in position "6", etc. Thus, the reactor comes to steady state mode of operation, if the vector of plutonium (the fraction of each plutonium isotope in the mass of plutonium) at each following step of the refueling of the active core remains constant (self-sufficient plutonium mode).

5. Results

Geometry parameters and isotopic composition of the model of high-power reactor core was assigned in JARFR to obtain the results on multiplication factor and mass of plutonium at the end of the time interval. Fuel reloading layout and modes of recycling were specified in REPRORYV code. Each fuel assembly was homogenized in the active core. All results correspond to fuel density 11.5 g/cm$^3$. The reactor was set to the critical state (Keff =~ 1) by changing plutonium content in the active core only in the initial period of time so the results should be viewed only from a methodological point of view. The methodological error of calculation of the multiplication factor in each case was equal to 10$^{-5}$. The rule “mass of the unloaded fuel assemblies should be equal to the mass of the loaded fuel assemblies in each of the cycles of refueling” was accepted for the formation of the new fuel composition by processing.

Figure 6 shows the dependence of the reactivity of the reactor core (in percent) on time (the life cycle of the reactor is 60 years) for different estimation of error in the results. The middle graph in this figure shows the average value, which was evaluated by REPRORYV code using the built-in module JARFR on each step. The top graph is an upper bound for the effect of errors in the mass of plutonium to Keff. To obtain this result the absolute error of plutonium was added to its entire mass on each iteration step. Obviously, the more reactor works, the larger the absolute deviation from the mean of Keff. The same procedure was done for the lower chart: here the error value of plutonium mass was subtracted from the entire mass of plutonium in each iteration step. The relative difference between the maximum and minimum value of Keff in relation to the average was 0.7%. So such an effect can be expected, if you taking into account uncertainties in the mass of plutonium.
Figure 6. The dependence of reactivity of the core on time (the life cycle of the reactor is 60 years) for different estimation of error in masses of plutonium in fuel.

In each fuel batch after 9 years it is necessary to add a smaller amount of plutonium to support the operation of the reactor (for the same mass of each fuel assembly, see table 1). From 4-th cycle the “excess” of plutonium accumulated in an amount of not more than 1%. So we can say that the reactor came to “steady-state” when the mass change of Plutonium between two steps is almost zero.

Table 1. Change (%) of the mass of plutonium during its production in each fuel batch during the reactor life cycle

| Cycle number | Batch # | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|-------------|--------|----|----|----|----|----|----|----|
|             | 1      | -3.0 | -1.9 | -1.2 | -0.7 | -0.4 | -0.3 |
|             | 2      | -2.5 | -1.6 | -1.1 | -0.6 | -0.4 | -0.2 |
|             | 3      | -2.6 | -1.7 | -1.1 | -0.6 | -0.4 | -0.2 |
|             | 4      | -2.8 | -1.9 | -1.1 | -0.6 | -0.4 | -0.2 |
|             | 5      | -1.9 | -1.5 | -0.8 | -0.6 | -0.3 | -0.3 |
|             | 6      | -1.7 | -1.3 | -0.7 | -0.5 | -0.3 | -    |
|             | 7      | -1.7 | -1.2 | -0.7 | -0.4 | -0.2 | -    |
|             | 8      | -1.5 | -0.9 | -0.7 | -0.3 | -0.3 | -    |
|             | 9      | -1.7 | -1.0 | -0.7 | -0.3 | -0.3 | -    |

6. Conclusion
The paper deals with evaluating of fuel handling in fast reactors in CNFC. To solve these problems, the REPRORYV program code is developed. It simulates the nuclide streams in out-of-reactor stages of the closed fuel cycle. Existed verified code JARFR is used for the calculation of neutron-physical characteristics of the core. Various options for nuclide streams are considered with a representative full-scale model of a fast reactor with sodium-cooled high-power. The changes of multiplication factor
and mass of plutonium in the closed nuclear fuel cycle for Russian fast high-power reactor with use of the REPRORYV code are evaluated. The maximum and minimum estimation of the effect of errors in the mass of plutonium to the multiplication factor was considered. The effect is equal to 0.7%.

This work was carried out within the framework of 5-100.

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