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NUCLEAR BURNING WAVE REACTOR: SMOOTH START-UP PROBLEM

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The search for a smooth start-up method preventing the excessive increase of neutron flux and power production in the prospective fast reactor at the stage of establishing the self-sustained nuclear burning wave (NBW) regime is carried out. The problem is studied by means of numerical simulation of the initiation and evolution of NBW in such a reactor. For this simulation we use the deterministic approach based on solving the non-stationary neutron diffusion equation using the effective multi-group approximation together with a set of burn-up equations for fuel components and equations of nuclear kinetics for precursor nuclei of delayed neutrons. The special composition of the ignition zone composition that provides a smooth start-up of the NBW reactor is proposed. The features of the initial stage of the NBW reactor are studied in detail.

KEY WORDS: fast reactor, nuclear burning wave, smooth start-up method, intrinsic safety, non-stationary diffusion equation.

РЕАКТОР С ВОЛНОЙ ЯДЕРНОГО ГОРЕНИЯ: ПРОБЛЕМА ПЛАВНОГО ЗАПУСКА

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Проведен поиск методики плавного запуска перспективного быстрого реактора, работающего в режиме волны ядерного горения, избегая чрезмерного увеличения потока нейтронов и мощности реактора на начальном этапе до выхода на стационарный режим бегущей волны. Проблема изучается с помощью численного моделирования, основанного на решении нестационарного уравнения диффузии нейтронов совместно с системой уравнений выгорания для компонентов топлива и уравнения ядерной кинетики ядер предшественников запаздывающих нейтронов с использованием эффективного много-группового приближения. Предложена специальная композиция зоны запала, которая обеспечивает плавный запуск реактора. Исследованы особенности начального этапа работы реактора с волной ядерного горения в этом случае.

КЛЮЧЕВЫЕ СЛОВА: быстрый реактор, волна ядерного горения, плавный запуск реактора, внутренняя безопасность, нестационарное уравнение диффузии.

РЕАКТОР З ХВИЛЕЮ ЯДЕРНОГО ГОРІННЯ: ПРОБЛЕМА ПЛАВНОГО ЗАПУСКУ

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Проведено пошук методики плавного запуску перспективного швидкого реактора, що працює в режимі хвилі ядерного горіння, уникаючи надмірного збільшення потоку нейтронів і потужності реактора на початковому етапі до виходу на стаціонарний режим хвилі, що біжить. Проблема вивчається за допомогою чисельного моделювання, заснованого на рішенні нестаціонарного рівняння дифузії нейтронів разом із системою рівнянь вигоряння для компонентів палива й рівняння ядерної кінетики ядер попередників запізнілих нейтронів з використанням ефективного багато-групового наближення. Запропоновано спеціальну композицію зони запала, що забезпечує плавний пуск реактора. Досліджено особливості початкового етапу роботи реактора із хвилею ядерного горіння в цьому випадку.

КЛЮЧОВІ СЛОВА: швидкий реактор, хвиля ядерного горіння, плавний запуск реактора, внутрішня безпека, нестаціонарне рівняння дифузії.

After the Chernobyl accident, the ensuring of real safety of the operation of nuclear reactors has become a foreground requirement made to their construction. In this context a great interest has been shown in some new concepts of nuclear fission reactors with the so-called intrinsic safety, in which the development of uncontrolled chain nuclear reaction is impossible due to the physical principles of their operation.

One of such concepts is based on the phenomenon of self-sustained nuclear burning wave (NBW) in a fast reactor (FR), which was discovered and preliminary studied by Lev Feoktistov [1, 2]. The non-linear self-organizing regime of the NBW arises owing to a high conversion ratio from fertile to fissile materials in the FR. The main advantage of this type FR is that it does not require a reactivity control and therefore the initial fuel composition of the reactor will evolve according to neutron-nucleus processes without an external intervention and any refueling or fuel shuffling during the full FR lifetime. The FR is automatically sustained in a state close to the critical one due to a specific type of the negative reactivity feedback, which is inherent to this regime ensuring the intrinsic safety of the NBW reactor.

Further, this concept was developed by several groups of investigators using different approaches and different names for this phenomenon: deflagration wave [3], criticality wave [4], CANDLE [5, 6], nuclear burning wave [7–11] etc. Lately, the most frequently used name is the Traveling Wave Reactor due to Bill Gates and TerraPower activity [12]. To simplify solving the essentially nonlinear non-stationary problem of neutron transport in such a system, Feoktistov [1, 2], as well as many authors later (see, e.g., [4–6]), considered a self-similar solution of this problem. This solution describes only a steady-state regime in the form of traveling NBW. This approach does not allow one to investigate the stability of the nuclear burning process in the reactor relative to different external perturbations, as well as to study the behavior of the FR in transient operation modes, such as the reactor start-up, emergency shutting down and restarting, partial coolant loss and so on.

In our previous works [7–11], a deterministic approach for describing the space-time evolution of the self-organizing regime of NBW in a critical FR has been developed in the framework of multigroup diffusion approximation. This approach is based on solving the non-stationary diffusion equation for neutron transport together with the burn-up equations for fuel components and the equations of nuclear kinetics for precursor nuclei of delayed neutrons, and has allowed us to simulate initiation of the NBW regime and to study its stability relative to distortions of the neutron flux as well as the mechanism of reactivity feedback inherent in this regime. In this approach, a number of studies of the NBW regime behavior were performed for the FR with metal fuel of U-Pu, Th-U and mixed Th-U-Pu cycles with taking account of typical volume fractions of fuel, constructional material (Fe) and different coolants (Na or Pb-Bi eutectic). In these studies, we used a rather simplified FR start-up scenario in which the NBW propagation in the breeding zone filled with the fertile material is initiated by an external neutron flux that irradiates a homogeneous ignition zone enriched with fissile isotopes. These calculations showed, in particular for the U-Pu metal fuel, a principal possibility of initiating the NBW, which then steadily propagates in the breeding zone during a long time period (decades). However, this simplified start-up scheme leads to an essential initial increase of the neutron flux in the ignition zone up to very high values that are unacceptable from the practical point of view and can even destroy the reactor. This initial neutron-flux increase develops slowly enough so that it could be prevented by means of conventional mechanisms of the reactor control in the ignition zone, but it is also interesting to elaborate a method of smooth start-up of this FR, which would include choosing a proper composition of the ignition zone that could ensure acceptable neutron flux values and a moderate power production. The aim of the present study is searching for such a method of smooth start-up of the NBW reactor with using the fuel of U-Pu cycle.

DESCRIPTION OF THE CALCULATION MODEL

In this research, we consider a critical FR of the cylindrical form with the metal fuel of U-Pu cycle in which the NBW would propagate along the cylinder axis (the axial direction). The FR under consideration consists of the ignition zone, that contains ^{238}U enriched with plutonium (the isotope composition of plutonium was ^{239}Pu : ^{240}Pu : ^{241}Pu : ^{242}Pu = 0.70 : 0.22 : 0.05 : 0.03) and the breeding zone adjacent to the ignition one, that is filled with the fertile ^{238}U isotope (see Fig. 1). The both zones also contain the constructional material Fe and the Pb-Bi eutectic coolant. In the simplified start-up scheme [7–11], both these zones are homogeneous with the sharp boundary between them. The initiation of the nuclear burning process in the system is done by an external neutron flux j_{ex}, that irradiates the end of the ignition zone. The initial configuration of the FR is chosen to be very close to the critical state by solving the corresponding criticality problem on reactor parameters that determine the variants of the size and the initial composition of the FR.

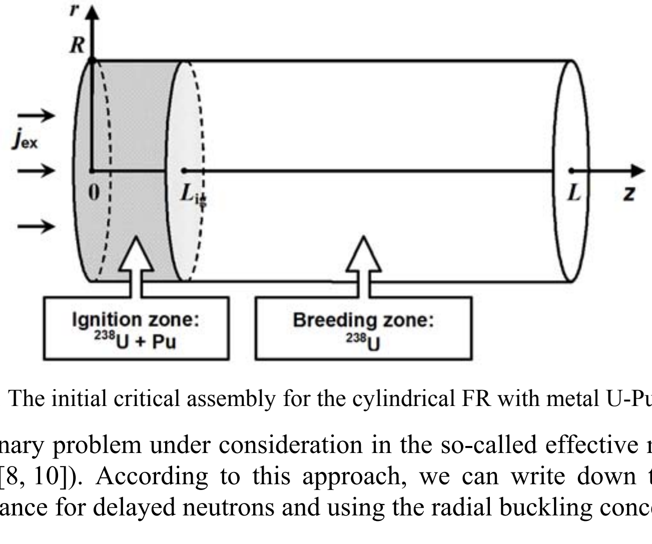

Fig.1. The initial critical assembly for the cylindrical FR with metal U-Pu fuel.

We solve the non-stationary problem under consideration in the so-called effective multigroup approach that was developed by us (see, e.g., [8, 10]). According to this approach, we can write down the one-group non-stationary diffusion equation with allowance for delayed neutrons and using the radial buckling concept in the following form

$$\frac{1}{v}\frac{\partial \Phi}{\partial t}+\frac{\partial V}{\partial z}+DB_r^2\Phi+\Sigma_a\Phi-(1-\overline{\beta})(\nu_f\Sigma_f)\Phi=\sum\nolimits_l\sum\nolimits_i\lambda_l^iC_l^i,\ \ V=-D\frac{\partial \Phi}{\partial z}, \tag{1}$$

where Φ is the scalar neutron flux; Σ_α, Σ_f are the effective macroscopic absorption and fission cross-sections and $D = 1/(3\Sigma_{tr})$ is the diffusion coefficient (Σ_{tr} being the effective macroscopic transport cross-section); $\nu_f\Sigma_f = \Sigma_l(\nu_f\sigma_f)_l$, where ν_f is the mean number of neutrons produced at a single nuclear fission event and l is the number of the fissioned nuclide; $\overline{\beta} = \Sigma_l\beta_l(\nu_f\Sigma_f)_l/(\nu_f\Sigma_f)$ is the effective fraction of delayed neutrons, $\beta_l = \Sigma_l\beta_l^i$, where β_l^i, C_l^i and λ_l^i are the fraction of delayed neutrons, the concentration and the decay constant of the precursor nuclei in the i-th group of the l-th fissioned nuclide, v is the one-group neutron velocity. The buckling coefficient is $B_r = 2.405 / (R + \delta_r)$, where δ_r is the extrapolation length. We use the value $\delta_r = 20$ cm, which corresponds to the case of a thick radial reflector of heavy material (U, Pb) [13].

The boundary conditions for the flux Φ at the FR ends ($z = 0$ and $z = L$) are:

$$\left(\Phi+2V\right)\Big|_{z=0}=2j_{ex},\ \ \left(\Phi-2V\right)\Big|_{z=L}=0. \tag{2}$$

For all values of z in the interval $0 \le z \le L$, an initial distribution of the neutron flux at the moment $t = 0$ is specified, which is chosen as a small scalar neutron flux for the initial critical assembly.

The fuel composition in the FR changes with the time course according to the nuclear transformation chain of the U-Pu fuel cycle. In this transformation chain, we consider, as in [7–11], ten nuclides which are numbered as follows: 1 – ^{238}U, 2 – ^{239}U, 3 – ^{239}Np, 4 – ^{239}Pu, 5 – ^{240}Pu, 6 – ^{241}Pu, 7 – ^{242}Pu, 8 – ^{243}Am, 9 – ^{241}Am, 10 – fission products (FP). The concentrations of these nuclides obey the following burn-up equations:

$$\frac{\partial N_1}{\partial t}=-\sigma_{a1}\Phi N_1, \tag{3}$$

$$\frac{\partial N_l}{\partial t}=-\left(\sigma_{al}\Phi+\Lambda_l\right)N_l+\left(\sigma_{c(l-1)}\Phi+\Lambda_{(l-1)}\right)N_{(l-1)}+\sigma_{c3}\Phi N_3\delta_{l,5},\ \ (l=2\div 8), \tag{4}$$

$$\frac{\partial N_9}{\partial t}=\Lambda_6N_6,\ \ \frac{\partial N_{10}}{\partial t}=\sum_{l=1,3\div 7}\sigma_{fl}N_l\Phi, \tag{5}$$

where $\sigma_{al} = \sigma_{cl} + \sigma_{fl}$, σ_{cl}, σ_{fl} are the effective one-group microscopic cross-sections of absorption, neutron radiative capture and fission for the l-th nuclide; $\Lambda_l = \ln 2/T_{1/2}^l$ and $T_{1/2}^l$ are the decay constant and the corresponding half-life for the l-th nuclide. Only the β-decay constants Λ_2, Λ_3 and Λ_6 are considered to be nonzero. At the initial moment, certain concentrations of nuclides are specified: $N_l(z, t = 0) = N_{0l}(z)$. In the calculations, we allow for the fission process for the nuclei with numbers 1, 3–7. Note that in our earlier studies we neglected the intermediate nuclide ^{239}Np burn-up, following [13]. The contribution of ^{239}Np burn-up can be essential for high values of the neutron flux. We use the kinetics equations for the concentrations of precursors of delayed neutrons in the approximation of one equivalent group of delayed neutrons (see, e.g., [7]). The method of solving the burn-up equations (3)–(5) and the nuclear kinetics equations is analogous to that described in [7].

The diffusion equation (1) is solved numerically using the conservative finite difference method (see, e.g., [14]) the implicit difference scheme by [15] with a variable time step, as is described in our previous works [7–11]. In the effective multigroup approach, at each time layer we also solve a multigroup stationary criticality problem with using the radial buckling concept for the assembly composition that changes with time according to the equations of fuel component burn-up. The calculations of the corresponding eigen functions are performed in the 26-group approximation, using the group neutron constant library [16]. The found group neutron fluxes are used to calculate the effective one-group microscopic cross-sections by the averaging procedure described in [13]. Thus, these cross-sections are corrected at each time step according to the neutron spectrum at each space mesh node. Solving the non-stationary problem in the effective multigroup approach with allowance for the mentioned alteration of neutron spectra can describe the evolution of the total (summed over groups) neutron flux accurately enough (see, e.g., [8]).

RESULTS OF CALCULATIONS

We have carried out a series of calculations of the space-time evolution of the NBW regime for different variants of the reactor parameters, which correspond to different compositions and geometrical dimensions of the initial critical FR assembly with using different variants of the ignition zone design. Below, we present the calculation results obtained for a variant of the NBW reactor with the simplified start-up scheme and, beside it, for the analogous FR with using the improved ignition zone design we found for a smooth start-up. First, let us discuss the results obtained for the simplified scheme. In Fig. 2*a* and *b* we present the axial distributions of some constituents of the composition of such a critical FR assembly and corresponding scalar neutron fluxes (normalized to the average energy release 20 W/cm^3). Calculations were performed in the 26-group and effective multigroup approximations for such geometrical dimensions of the reactor: the FR length $L = 500$ cm, the cylinder radius $R = 105$ cm, the axial size of the ignition zone

L_{ig} = 72.75 cm.

We have chosen the following values of the volume fractions of fuel, $F_{\text{fuel}} = 44\%$, the constructional material Fe, $F_{\text{Fe}} = 20\%$, and the Pb-Bi coolant $F_{\text{cool}} = 36\%$. The value of the fuel void fraction $p = 0.2$. The concentration of plutonium in the ignition zone was chosen at 10%.

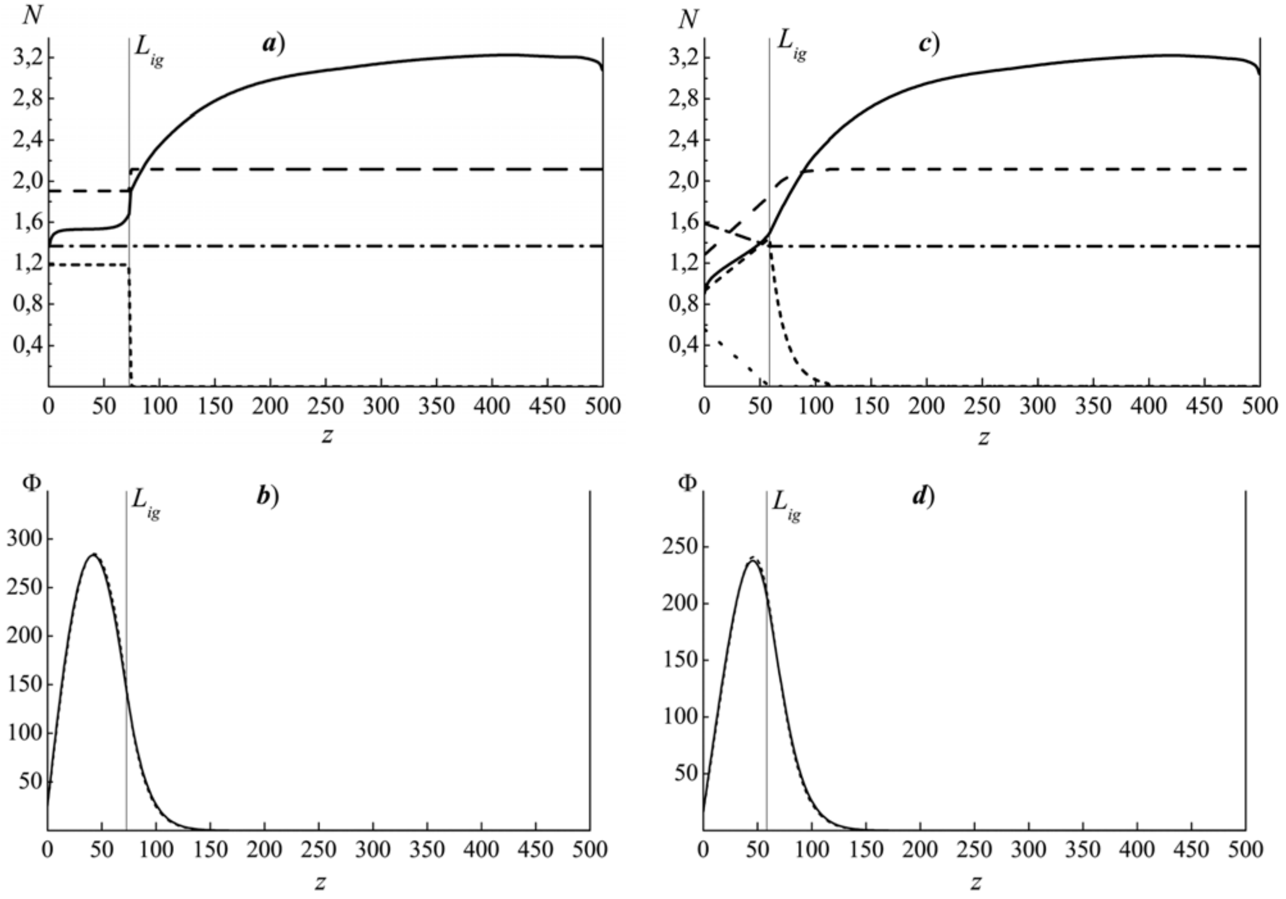

Fig. 2. Axial profiles (z in cm) for the initial critical FR compositions with the simplified (left) and improved smooth (right) start-up schemes.
a) and *c*) presents the concentrations N (10^{-3} b^{-1}cm^{-1}) of the actual N_4 (short dashes) and equilibrium N_{eq} (solid line) values for ^{239}Pu; and other values divided by 8: N_1 (dashes) for ^{238}U, $N_{\text{Pb-Bi}}$ (dash-dotted) for Pb-Bi and N_{Ta} (dots) for ^{181}Ta; *b*) and *d*) presents the neutron flux Φ (b^{-1}day^{-1}) in the effective multigroup approximation (dashes) and 26-group calculation (solid line).

The comparison of calculations of the neutron flux summed over 26 groups with the flux calculated in the effective multigroup approximation shows that the latter calculation reproduces the exact result in the multigroup approximation quite accurately. From Fig. 2b, it follows that in the simplified scheme the maximum neutron flux is reached approximately in the ignition zone center. The neutron flux on “the tail” of its axial distribution, which illuminates the breeding zone and determines the speed of isotope ^{239}Pu production near the border of the ignition and breeding zones, is not large enough. From Fig. 2a, one can see the ratio between the actual initial ^{239}Pu concentration and its equilibrium value, which is able to ensure, according to [1, 2], the self-sustained burning process and the NBW formation in this FR. The equilibrium value, $N_{eq} = \sigma_{c1}N_1 / (\sigma_{f4} + \sigma_{c4})$, is determined as the value of ^{239}Pu concentration to which it tends asymptotically with the time course under a constant irradiation of the fuel by a neutron flux [1, 2].

The chain reaction in this FR with the simplified start-up scheme is initiated by an external neutron flux with intensity $j_{ex} \approx 10^{13}$ cm^{-2} s^{-1} which is turned off at $t = 30$ days. As a result, after the initial period of approximately 2 years a stationary wave regime of nuclear burning is set in the FR under consideration. Figs. 3a,b present the corresponding time dependences for the NBW velocity V and the integral power of energy production P_I. Note that for the chosen FR radius and the breeding zone composition, the steady NBW regime has a rather small velocity of the wave (~ 0.05 cm/day) and a long reactor campaign (~ 20 years). The reactor power value at the stage of the stationary burning wave is ~ 3 GW. However, at the very beginning of the campaign, when the wave front is formed near the ignition zone border, there is a huge increase in the neutron flux in the ignition zone to values that are more than an order of magnitude higher than the flux value at the steady NBW stage, which is unacceptable from a practical point of view. In Fig. 3a, this effect is manifested by a sharp surge of the velocity V at $t \approx 150$ days which is also accompanied by a very high increase of the reactor power P_I up to values of ~ 30 GW (Fig. 3b).

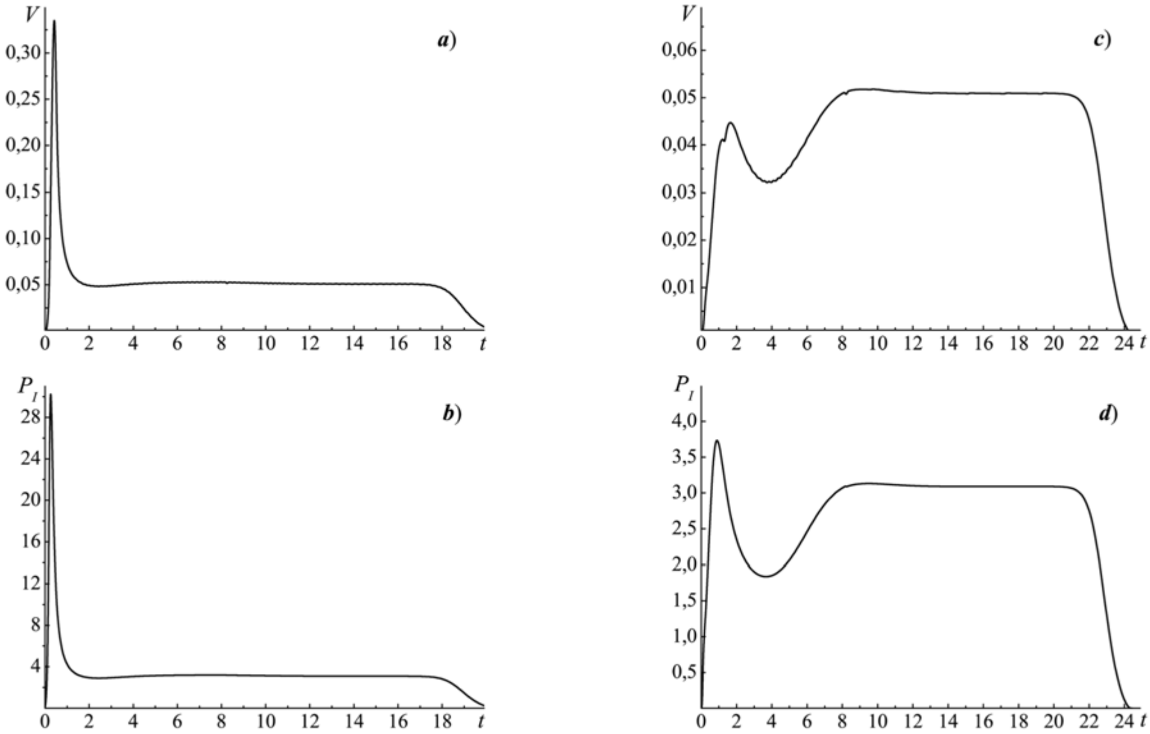

Fig. 3. The NBW velocity V (a, c; cm/day) and the total energy production power P_I (b, d; GW) versus time t (years) for the FR variants with the simplified (left) and improved smooth (right) start-up schemes, whose critical configurations are shown in Fig. 2.

For a better understanding of the process of forming the NBW front and the origin of the above-described unacceptable phenomena, in the left part of Fig. 4 we consider the space evolution of the axial distributions of the neutron flux and main fuel components at the initial stage of the nuclear burning in the FR with the simplified start-up at several time moments at regular intervals (40 days) during the first year of the FR operation. It is seen from Fig. 4a, that at $t < 150$ days (the moments: $t_1 - t_3$) a large increase of the flux **Φ** occurs, while the position of its maximum is almost the same. Then (the moments: $t_4 - t_8$), the **Φ** value gradually decreases to a level close to its value in the NBW and the position of the flux maximum gradually moves to the breeding zone, i.e. the wave starts to move. Fig. 4b shows that the time interval $t_1 - t_4$, during which the flux **Φ** has the largest values, corresponds to the most radical changes of the axial profile of the ^{239}Pu concentration, which consist in its rapid production in the breeding zone near the ignition zone. This leads to creating its distribution form characteristic of the wave front. Then, with a decrease of the flux **Φ** during the time interval $t_4 - t_8$, slower changes of the ^{239}Pu profile and the final formation of the wave front occur. From Fig. 4*c*, it is seen that during the time interval $t_1 - t_4$, the most rapid transformation and burning of the fertile ^{238}U isotope are observed, and at the interval $t_4 - t_8$ these processes are slower but the NBW front moves further into the breeding zone. From the above-mentioned facts, we can draw the following conclusions. For the simplified type of the ignition zone, a too radical rearrangement of the axial distribution profiles of the main fuel components is necessary to form the NBW front. However, the neutron flux fraction that irradiates the most important region of the ^{239}Pu production at the breeding zone border is rather small (Figs. 2a and 4a). A characteristic feature of the self-organizing process of nuclear burning in FR of this type is that the system itself adjusts in such a way that provides the neutron flux sufficient for the formation of NBW, which leads to its excessive growth.

The observed excessive increase of the neutron flux and energy production is rather slow, and it could be suppressed by a conventional system of external reactor control. However, this method would deprive this FR of its attractive features of self-regulation at the early stage of the NBW initiation, which would be prolonged for many years. Therefore, in this paper, we set the task to provide an acceptable passage of the initial stage of the FR operation without violating the self-regulating nature of the burning regime by choosing an optimal composition of the enriched ignition zone itself. When choosing the ignition zone structure, we aim, firstly, to provide the displacement of a large part of the neutron flux distribution to the breeding zone, and secondly, to facilitate the necessary rearrangement of the initial composition of the ignition zone during the NBW front formation.

It should be noted that in [17], to solve the problem of the smooth start-up of the CANDLE reactor, the authors tried to bring the initial reactor composition maximally close (in terms of k_{inf}) to the composition characteristic of the steady NBW stage. The calculation method, used in [17], is based on the self-similar solution of diffusion equation for neutron transport [5, 6]. This approach is quite sufficient for description of the steady NBW stage; however, it is unable to describe the non-stationary processes at the initiation of the NBW regime adequately.

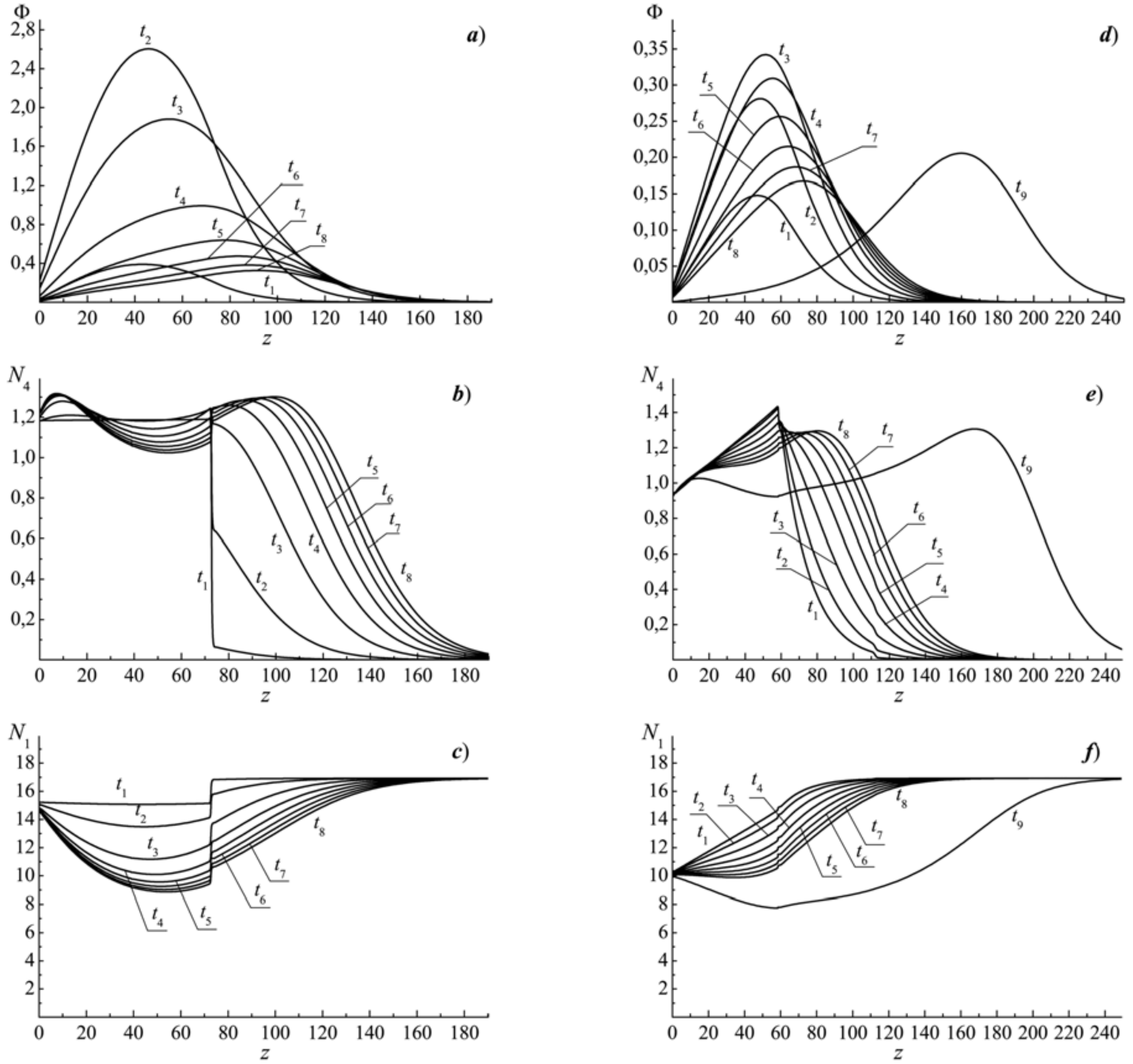

Fig. 4. Initial evolution of axial profiles (z in cm) near the ignition zone for the neutron flux Φ ($\times 10^{17}$ cm^{-2} s^{-1}) and the ^{239}Pu and ^{238}U concentrations N_4 and N_1 ($\times 10^{21}$ cm^{-3}) for the FR with simplified start-up scheme(left or a, b, and c) at the time moments $t_1 = 40$, $t_2 = 80$, $t_3 = 120$, $t_4 = 160$, $t_5 = 200$, $t_6 = 240$, $t_7 = 280$ and $t_8 = 320$ days, and with the improved smooth start-up (right or d, e and f) at the moments $t_1 = 100$, $t_2 = 200$, $t_3 = 300$, $t_4 = 400$, $t_5 = 500$, $t_6 = 600$, $t_7 = 700$, $t_8 = 800$ and $t_9 = 3000$ days.

In this paper, we have considered a number of possible variants for the ignition zone structure to optimize the regime start-up stage. On the basis of this analysis, we have proposed an improved ignition zone configuration for this FR, the use of which we consider below.

In the right part of Fig. 2, we present the characteristics of the initial critical FR assembly with the improved ignition zone of this type. The main parameters of the considered FR are the same as presented above, except the ignition zone. Now the plutonium content in the ignition zone is not constant, but varies by the linear law: $N_{\mathrm{Pu}} = N_{\mathrm{f}}\,[e_1 + z\,(e_2 - e_1)\,/\,L_{ig}]$, where N_{f} is the concentration of the fuel nuclides in the breeding zone, and the coefficients e_1 and e_2 characterize the fuel enrichment in the ignition zone. In the breeding zone, in the layer adjacent to the ignition zone, $L_{ig} < z < L_{ig} + 4\Delta$, we add an exponential “tail” enriched with plutonium: $N_{\mathrm{Pu}} = N_{\mathrm{f}}\,e_2 \exp[-(z - L_{ig})\,/\,\Delta]$. This “tail” essentially facilitates forming the NBW front. The fuel volume fraction in the ignition zone varies linearly: $F_{\mathrm{f}}^{(\mathrm{ig})}(z) = F_{\mathrm{f}}\,[u_1 + (1 - u_1)\,z\,/\,L_{ig}]$. The decrease of the fuel fraction in the ignition zone is chosen in such a way that the corresponding content of ^{238}U would ensure the equilibrium values N_{eq} being nearly at the level of the actual ^{239}Pu concentration (Fig. 2c).

The volume freed from the fuel is filled up with a mixture of the Pb-Bi alloy, which weakly absorbs neutrons, and ^{181}Ta that is used as an absorbing material in fast reactors [13]. The relative volume fraction of ^{181}Ta, $F_{\mathrm{Ta}} = 0.58$, is chosen so that this mixture, in its absorption properties, could imitate the presence of fission products on the back side of the wave. An important effect of introducing this absorber in the ignition zone is shifting the maximum of the initial distribution of the neutron flux (Fig. 2d) in the direction of the breeding zone. Thus, an essential fraction of the flux falls on the region of forming the NBW front in the breeding zone. The values of the above-mentioned parameters of the ignition zone used in the case under consideration are as follows: $L_{ig} = 58.5$ cm, $e_1 = 0.079$, $e_2 = 0.122$, $\Delta = 13.5$ cm, $u_1 = 0.687$.

Here, we also use a more effective scheme of bringing the initial neutron field in the FR to a chosen optimal level by using an additional absorbing ^{181}Ta regulator in the ignition zone. The initial configuration of FR is chosen with a little reactivity excess, $\rho \sim 10^{-4}$. The system is brought to a subcritical state by the additional tantalum absorber, which is gradually withdrawn from the system after turning the external neutron flux ($j_{ex} \approx 10^{11}$ cm^{-2} s^{-1}), until the neutron field in the FR reaches the chosen level. Note that in this case we can use a significantly lower value of j_{ex}. According to this, the additional concentration of ^{181}Ta varies with time as: $N_{\mathrm{Ta}}(t) = N_{\mathrm{Ta}}^{(0)}(T - t) / T$. In the presented calculation we put $N_{\mathrm{Ta}}^{(0)} = 2.5 \cdot 10^{-4}$ b^{-1}cm^{-1}, $T = 40$ days, and the neutron flux was brought to ~ 80% of its level in the NBW regime, after which the regulator withdrawal was stopped and j_{ex} was turned off.

In the right part of Fig. 3, we present the time dependencies of the NBW velocity V and total energy production power P_l during the reactor campaign for the FR with the above-described improved ignition zone. Fig. 3d shows that employing the improved start-up scheme allows us to prevent the exorbitant increase of the reactor power. There is no great surge of velocity value V (Figs. 3c and 3a), as well.

The NBW regime is formed slightly slower (for about 2.5 years) than in the case presented in the left part of Fig. 3. Note that the wave moves, at first, with a less velocity and a less power P_l than at the stage of the steady NBW regime, which, probably, is due to the influence of edge effects from the ignition zone residuals. Finally, the NBW reaches the steady regime in several years, which is not an essential disadvantage of the considered scheme, because at this stage the FR power should be adjusted according to current demands by some proper methods (e.g., by changing the radial reflector efficiency), which are not considered here.

In the right part of Fig. 4, we consider the space-time evolution of the distributions of neutron flux and main fuel components at the beginning of this FR campaign. We present the axial profiles of these quantities for several initial moments of time $t_1 - t_8$ of the reactor operation at regular intervals (100 days) and for the moment t_9, when the NBW has reached the steady regime. Unlike the left part of Fig. 4, here there is no excessive increase of the neutron flux, and the rearrangement of the system components and the formation of the wave front occur smoothly. During the interval $t_1 - t_8$, the maximum of the neutron flux gradually shifts toward the breeding zone. Note also that Figs. 4e and 4f show that the initial profile of the ignition zone, in fact, imitates roughly the form of NBW front. It is interesting that, for the moment t_8, the ^{239}Pu and ^{238}U distributions in the wave front coincide with those for the moment t_9 in the steady regime, but the level of the neutron flux at t_8 is slightly lower, which corresponds to the initial slowdown of the burning wave mentioned above.

CONCLUSION

The results of studies of establishing the stage of self-sustained NBW regime in the prospective FR under consideration show that an excessive increase of neutron flux and power production, that is mainly due to a lack of adequate amount of fission products at the ignition stage, as compared with the steady state of the NBW regime, can be prevented by using a special smooth start-up method proposed in this paper. This method is based on the selection of the ignition zone composition featured by the fuel component distribution and neutron flux profile roughly similar to the corresponding characteristics inherent to the steady state regime of the NBW propagation in FR. The absence of fission products at the initial stage of the reactor start-up compensate with adding a certain amount of the metallic tantalum, which is a good neutron absorber. The composition and spatial distribution of the fuel components (uranium and plutonium) and absorber (tantalum) in the ignition zone are selected in a way that provides a significant displacement of the neutron flux in the initial assembly of FR to the border between ignition and breeding zones.

The problem is studied by means of the numerical simulation of initiation and evolution of the NBW in a cylindrical FR with metallic U-Pu fuel in the framework of the deterministic approach based on solving the non-stationary diffusion equation of neutron transport together with a set of burn-up equations for fuel components and equations of nuclear kinetics for precursor nuclei of delayed neutrons with making use of the effective multigroup approximation and radial buckling concept.

Basing on this calculation scheme, we have also considered a gradual initial bringing of the neutron flux to an optimum level by using an additional tantalum regulator in order to ensure a relatively short time period of forming the self-sustained NBW regime. This scenario also provides a reduction of the intensity and duration of the external neutron flux used for initiating the NBW regime. The features of the initial stage of operation of the NBW reactor with improved ignition zone are studied in detail. It is shown that using the proposed start-up method makes it possible to suppress the initial increase of neutron flux almost by a factor of ten in comparison with the simplified start-up scheme and to get its value very close to the neutron flux value at the steady NBW regime (Figs. 4a,d). The residual variation of the neutron flux which takes place at the start-up of FR is very slow and has a small enough amplitude and, therefore, can be easily removed in a real reactor by means of control rods or a corresponding change in the efficiency of the radial reflector.

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