NUCLIDE COMPOSITION DYNAMICS IN A SUBCRITICAL REACTOR DRIVEN BY A PROTON BEAM

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The numerical simulation results of nuclide composition time dynamics in a subcritical reactor blanket are given. A cylindrical subcritical reactor is driven by a high-energy proton beam injected along the radius into the reactor blanket. The initial blanket substance was the fertile uranium with different energetic plutonium concentration.

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1. INTRODUCTION

Now high-current proton accelerators of high energies are used for developing of powerful neutron sources [1]. Such neutron sources are supposed to apply for driving of subcritical reactors, in which the reactivity accidents are eliminated, for transmutation of long-lived radioactive nuclides contained in spent fuel of modern industrial thermal reactors, and also for applied and fundamental researches [2-4].

The neutron generation in these sources is based on usage of nuclear cascade processes (spallation), which occur in collisions of relativistic protons with heavy element nuclei [4]. The maximal neutron yield δ_{sp} per one proton stopping in a substance is for a uranium target. For proton energy $W \geq 1$ GeV the specific energy consumption W/δ_{sp} to produce one neutron achieves of the minimum and approximately is constant with the energy growth [5]. Therefore in many projects of electronuclear devices the proton accelerator energy is chosen $W \sim 1$ GeV, taking into account financial expenditures and accelerator construction complexities [1].

If the subcritical reactor power is given then the proton beam current may be minimized when a spallation-target is natural or fertile uranium due to the high value of δ_{sp}. Usage of targets from actinides allows one to increase the reactor energy efficiency as a result of additional fission of actinides by beam protons. Any fission of an actinide nucleus by a proton gives the same energy release as one by a neutron ($E_f \cong 200$ MeV). The cross-sections of these processes for considered proton energies exceed 1 barn [6].

In the paper [7] a model of a subcritical cylindrical reactor with uranium-plutonium blanket and radial proton beam injected directly in the blanket substance (combined target) had been considered. For the spherically symmetric distribution of the strength of the external neutron source generated by a proton beam, the analytical expression for the neutron flux spatial distribution had been obtained depending on the reactor dimensions, beam parameters and blanket multiplication properties. The expression for the neutron flux was obtained in one-group diffusion approximation [8].

In the present work the nuclide composition dynamics of uranium-plutonium blanket irradiated by a proton beam was studied.

2. NEUTRON FIELD IN BLANKET WITH COMBINED TARGET

In Fig.1, the model of subcritical cylindrical reactor with a combined target and radial injection of a proton beam is given. The external neutron source region 1, Fig.1, generated by a proton beam, is shown as a sphere of radius R_{sp}. Volume V_{sp} of this sphere is taken equal to volume $V_b = \pi r^2_b l_b$ of region occupied by a stopping cylindrical proton beam in the blanket substance (r_b is the beam radius, l_b is the proton path length in the blanket).

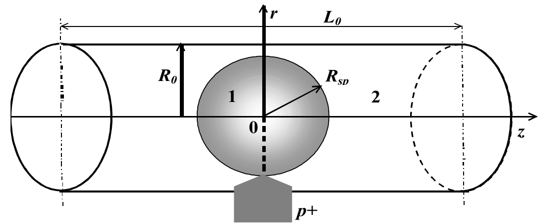

Fig.1. Model of subcritical reactor with combined target:1-spallation region, 2-external burning region

The external neutron source specific strength $S_0(r,z)$ is supposed uniformly distributed over the sphere of $(r^2+z^2)^{1/2} \leq R_{sp}$. In this case $S_0 = I_b\delta_{sp}/eV_{sp} = I_b\delta_{sp}/\pi r_b^2 e l_b$, where I_b is the beam current, e is the proton charge.

For a homogeneous blanket in one-group diffusion approximation the spatial distribution of scalar neutron flux $\Phi(r,z)$ can be represented as [7]:

$$\Phi(r,z) = \frac{1}{\Sigma_a}\sum_{j=0}^{\infty}\sum_{i=1}^{\infty}\frac{S_{ij}}{\left(1+L_D^2B_{ij}^2-K\right)}J_0\left(\frac{k_{0i}}{R_a}r\right)\cos\frac{(2j+1)\pi z}{2H}, \qquad (1)$$

where $S_{ij} = \dfrac{4S_0R_{sp}}{HR_a^2B_{ij}^2J_1^2(k_{0i})}\left[\dfrac{\sin(R_{sp}B_{ij})}{R_{sp}B_{ij}} - \cos(R_{sp}B_{ij})\right]$,

$B^2_{ij} = (k_{0i}/R_a)^2 + ((2j+1)\pi/2H)^2$, L_D is the neutron diffusion length, $H = (L_0/2) + 0.71\cdot\lambda_{tr}$, $R_a = R_0 + 0.71\cdot\lambda_{tr}$, λ_{tr} is the neutron transport length [8], $J_0(x)$, $J_1(x)$ are the Bessel functions of the zeroth and first orders, k_{0i} is the i-th root of the zero order Bessel function; K is the neutron multiplication factor in an infinite medium, Σ_a is the microscopic neutron absorption cross-section.

From the expression (1) it follows, that the neutron flux is $\Phi(r,z) \sim I_b\cdot\delta_{sp}$, i.e. it is proportional to a beam current I_b and neutron yield δ_{sp} for the given beam radius r_b and proton energy W (accordingly l_b). When $K_{ef} = K - L_D^2B_{10}^2 \to 1$ reactor goes to criticality, and accordingly $\Phi(r,z) \to \infty$ (K_{ef} is the neutron effective multiplication factor, $B_{10}^2 = (2.405/R_a)^2 + (\pi/2H)^2$ is the reactor geometrical factor [8]). In paper [7] it was shown, that for $K_{ef} \to 1$ dimensions of resulting neutron field are essentially increasing, if the reactor sizes $R_0 >> L_D$ and $(L_0/2) >> L_D$. For low K_{ef} the dimensions of neutron field region are in general determined by the sizes of a region occupied by an external neutron source (proton beam). Simultaneously when $K_{ef} \to 1$ the neutron flux is increasing also.

For the calculation of neutron group constants, which are needed for the estimation of the neutron flux value, the evaluated neutron data library ENDF/B-VI of Brookhaven National Laboratory of USA was used. The neutron energy spectrum in the blanket was supposed similar to the neutron spectrum in the fast reactor with the metal uranium-plutonium fuel and sodium coolant [8].

In Fig.2 the plutonium concentrations C(%) in the fertile uranium blanket are shown, which are necessary to reach the given neutron effective multiplication factor K_{ef}, for several radii R_0 and lengths L_0 of the reactor. The plutonium isotope composition was supposed equal to one in the spent fuel of the industrial thermal reactor, such as *VVER-1000*, with the burnup ~ *40* MW·day/kg and *10*-year's cooling [9]. How it follows from Fig.2, for the reactor radius of R_0=40 cm and lengths of L_0=80…240 cm the reactor goes to criticality $K_{ef}=1$, when the plutonium concentration is C=11.4…10.7%. For the reactor sizes shown in Fig.2, the main neutron leakage occurs over the side surface of the blanket.

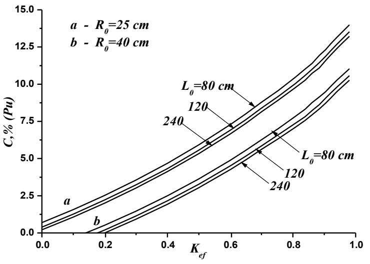

Fig. 2. Plutonium concentrations C(%) versus K_{ef} for several radii R_0 and lengths L_0 of subcritical reactor blanket

The dependences of the neutron flux *Φ(0,0)* at the reactor center on a proton beam radius r_b are presented in Fig.3 for several values of K_{ef}. The absolute neutron flux values *Φ(0,0)* in Fig.3 are reduced to the beam current I_b.

As it follows from Fig.3, the relative decreasing of the neutron flux *Φ(0,0)* at the blanket center with the beam radius r_b growth for the given beam current of I_b depends essentially on K_{ef}. At low K_{ef}, when the resulting neutron field is defined by spallation neutrons, the strong dependence of the neutron flux *Φ(0,0)* on the beam current density $J_b=I_b/\pi r_b^2$ is observed. At $K_{ef} \to 1$ the neutron field is in general determined by the secondary neutrons due to blanket material fission that results in weak dependence of the neutron flux on the current density J_b, Fig.3.

3. NUCLIDE COMPOSITION DYNAMICS UNDER PROTON IRRADIATION

If the performances of the neutron field *Φ(r,z)* are known for given proton beam parameters, it is possible to calculate the evolution of nuclide composition of the blanket material due to irradiation both by protons and neutrons generated. For this process simulation the chain of actinide transformations induced by neutrons and radioactive decays of nuclei was restricted with long-lived americium isotopes ^{241}Am, ^{243}Am [8].

The process of blanket material irradiation directly by high energy protons is complex one, which results in nuclear fragmentation and multiple particle production [4]. Its simulation is based, as a rule, on Monte-Carlo methods [10].

In the present work from many reaction channels produced by proton irradiation of blanket substance in the external neutron source region 1, Fig.1, it was taken into account only actinide fission induced by protons. Fission cross-sections of uranium, neptunium, and plutonium isotopes are studied enough and in the proton energy region W≤10 GeV have approximately identical dependences on W [6].

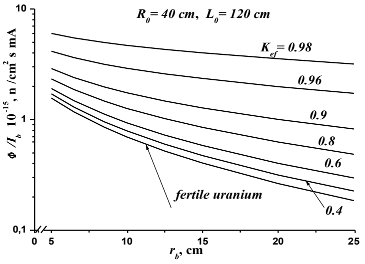

Fig. 3. Neutron flux Φ(0,0) in the spallation region center versus beam radius r_b for different K_{ef}

If the neutron field *Φ(r,z)* is stationary and taking into account above restrictions, the nuclide composition dynamics depending on irradiation time t may be presented by the system of the ordinary differential equations [2,11]:

$$\begin{aligned} dN_i(r,z,t)/dt = -\left[\sigma_i^a \Phi(r,z) + \sum_j \lambda_{ij}\right] N_i + \\ + \sum_{j \neq i} \left[\sigma_{ji}^c \Phi(r,z) + \lambda_{ji}\right] N_j - J_b N_i \sigma_i^p / e \end{aligned}, \qquad (2)$$

where N_i is the density of i-kind nuclei, $\sigma^a{}_i$ is the neutron absorption cross-section by i-nuclei, $\sigma^c{}_{ji}$ is the neutron capture cross-section by j-nuclei with producing of i-nuclei, λ_{ij} is the decay constant of i-nuclei with forming of j-nuclei, $\sigma^p{}_i$ is proton fission cross-section of the i-actinide averaged over proton range in the blanket.

The last term in Eq.2 describes the actinide density change in the region 1, Fig. 1, produced by proton fission of the nuclide. This process rate is proportional to the beam current density J_b. Outside of the beam region, i.e. $(r^2+z^2)^{1/2}>R_{sp}$, the current density is J_b=0. In the evolution equation for the fission product density it was assumed that the actinide fission both by protons, and neutrons, gives two nuclear fission fragments.

The analysis of Eqs. (1) and (2) shows, that, if the decay constants λ_{ji} and λ_i are small, i.e. the half-life periods essentially exceed the irradiation time t, the isotope density behaviour depends only on the product of the beam current I_b and irradiation time t, i.e. on the total proton beam fluence $F_b=I_b \cdot t$.

For the reactor active zone center ($r=0, z=0$) the dependences of densities N_i of uranium-238, fission products (*FP*), isotopes of plutonium and americium on the proton beam fluence are shown in Figs.4 and 5. The initial nuclide composition of the blanket is the fertile uranium-238; proton energy is W=1 GeV, the beam radius is r_b=5 cm. The solid curves in Fig.4 and 5 correspond to blanket irradiation by the beam with the current of I_b=1 mA, and the markers are for the beam current of 10 mA. The dependences shown in Fig.4 and 5 have been obtained by the numerical solution of the system of equations (2).

It is follows from Fig.4 and 5 that the behaviour of ^{238}U, ^{239}Pu, ^{240}Pu and fission products (*FP*) densities does not depend on time irradiation mode, and is determined by the total proton beam fluence. Very strong dependence on the time irradiation mode is observed for density of ^{241}Am, Fig.5. This isotope is the result of β-decay of ^{241}Pu isotope, which the half-life period is 13.2 years [8].

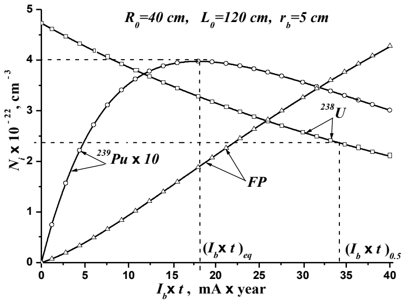

Fig.4. Uranium-238, plutonium-239 and fission products (FP) densities N_i *versus the proton beam fluence* $(I_b \times t)$ *in the blanket center; the initial fuel is the fertile uranium*

During irradiation of the fertile uranium blanket the uranium density is monotonically decreasing, and the fission products (*FP*) density monotonically is increasing, Fig.4. The density of ^{239}Pu, which does not contain in the parent blanket substance, initially is monotonically increasing (*breeding stage*), achieves the equilibrium concentration C_{eq} and further is decreasing (*transmutation stage*) with the beam fluence growth. The initial breeding rate of ^{239}Pu ($t=0$) makes 2.62 kg/mA·year.

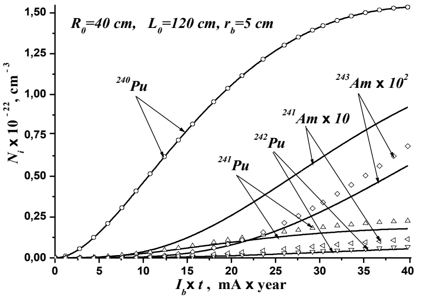

Fig. 5. Plutonium and americium isotope densities N_i *versus the proton beam fluence* $(I_b \times t)$ *in the blanket center; the initial fuel is the fertile uranium*

In the burning process stimulated by the proton beam in the subcritical blanket (Figs.4, 5), it is possible to note the some reference beam fluence values. Firstly, it is the fluence value of $(F_b)_{eq}=(I_bt)_{eq}$, when the equilibrium concentration of ^{239}Pu is reached. For considered reactor and beam parameters this fluence is $(F_b)_{eq}\approx$ 18 mA·year. From the Eq.2 it follows that the plutonium-239 equilibrium concentration in the beam region is $C_{eq}=N_2/N_1=\sigma^c{}_1/(\sigma^a{}_2+\sigma^p{}_2(J_b/e\Phi))$, and outside of this region, where the current density is J_b=0, $C_{eq}=\sigma^c{}_1/\sigma^a{}_2$. Here indexes 1 and 2 correspond to ^{238}U and ^{239}Pu accordingly.

Secondly, it is necessary to note the fluence value $(F_b)_{0,5}=(I_bt)_{0,5}$, when the half of uranium nuclei is burned up. According to Fig.4 this value is $(F_b)_{0,5}\approx$34 mA·year.

As for Minor Actinides from Fig.5 it follows that only ^{240}Pu isotope achieves the equilibrium concentration in the beam fluence range of $F_b\leq$40 mA per·year being considered.

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ДИНАМИКА НУКЛИДНОГО СОСТАВА ПОДКРИТИЧЕСКОГО РЕАКТОРА, УПРАВЛЯЕМОГО ПРОТОННЫМ ПУЧКОМ

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Приведены результаты численного моделирования изменения во времени нуклидного состава бланкета подкритического реактора при радиальной инжекции протонного пучка. Веществом бланкета является обеднённый уран с различной концентрацией энергетического плутония.

ДИНАМІКА НУКЛІДНОГО СКЛАДУ ПІДКРИТИЧНОГО РЕАКТОРА, ЩО КЕРУЄТЬСЯ ПРОТОННИМ ПУЧКОМ

Є.В. Гусєв, П.О. Демченко, Л.І. Ніколайчук

Надано результати чисельного моделювання зміни з часом нуклідного складу бланкета підкритичного реактора з радіальною інжекцією протонного пучка. Матеріалом бланкету є збіднений уран з різною концентрацією енергетичного плутонію.