SLOW BURNING IN A SUBCRITICAL REACTOR DRIVEN BY A PROTON BEAM*

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PACS: 28.52.-s; 52.59.-f

1.INTRODUCTION

The experience of nuclear power reactor operation with uranium and plutonium isotope fuel fissioned by neutrons has shown that future extensive nuclear power usage is impossible without solutions of some scientific, technological, and ecological problems. They are safety and reliability of modern reactors operating in the critical mode; utilization of radioactive waste produced by them; inclusion into the fuel cycle thousands of tons of fertile uranium-238 that is the cleaning rejects at enrichment plants as well as thorium-232 [1,2].

The most dangerous accidents of nuclear reactors are results of the uncontrolled growth of the effective criticality factor K_{ef} and subsequent heat reactor run away which leads to the following burst out and ejection of the great amount of radioactive products in the environment. To ensure the nuclear reactor operation for a long time, the abundant amount of fissile material is loaded in it. In this case the positive reactivity $(K_{ef}-1)/K_{ef}$ is compensated by control rods, fabricated from the material absorbing abundant neutrons. Thus, all modern power reactors both with thermal and fast neutrons are potentially dangerous objects [3,4].

The most dangerous accidents with uncontrolled growth of K_{ef} can be excluded if a nuclear reactor operates in a subcritical mode, i.e. under condition of $K_{ef}<1$ [5]. However, to get a stationary in time neutron flux when $K_{ef}<1$, it is necessary to introduce an external neutron source in a multiplication reactor medium. However, the initial neutrons must not be generated due to fuel nuclide fission by neutrons. Now, it is assumed that the most powerful external neutron sources may be created on the base of both thermonuclear reactions, and at collisions of high-energy protons ($W\geq 1$ GeV) with nuclei of heavy elements (tungsten, lead, bismuth, thorium, uranium) [6,7].

As it is known about *80%* of released fusion energy is removed from *D-T* plasma by the fast neutrons with energy of $E\approx 14$ MeV. The kinetic neutron energy may be converted into electrical power with 30-35 % efficiency only due to the neutron moderation in a substance and released heat removed by a coolant into a stream generator. More effective thermonuclear neutron utilization is their absorption in a subcritical blanket from uranium-238 or thorium-232 surrounding a thermonuclear reactor [7]. Fissile plutonium-239 or uranium-233 produced in the blanket may be removed and used for the fuel enrichment of usual power reactors. Moreover, when liquid lithium is used for a blanket cooling, tritium will be produced in it, which is a thermonuclear reactor fuel.

The second important application of fusion neutrons is the transmutation of long-lived radioactive nuclides which are wastes of the fuel cycle of power fission reactors, especially of neptunium, plutonium, americium, curium isotopes (*Minor Actinides*) with half-life of hundred and thousand years [2]. At present, thermonuclear reactor applications, in particular with magnetic confinement (*Tokamak*), are considered for transmutation of radionuclides, which are produced in the fuel cycle of power fission reactors [8]. Thus, in future the general nuclear power industry on the base of nuclear fusion reactors as well as fission ones may be created. In this case, the fission reactors will supply with power the thermonuclear reactor systems.

Unfortunately, engineering and technological difficulties and high costs of scientific developments do not permit to create powerful fusion neutron sources on the base of magnetic or inertial plasma confinement in the nearest future.

Now some progress has been reached in creation of powerful fast neutron sources using cascade processes (spallation) in collisions of high-energy protons with heavy nuclei [6]. In collisions of the intermediate and high-energy protons of $W\geq 0.5\text{-}3$ GeV with heavy nuclei up to *40* neutrons per one proton may by generated in dependence on the proton energy and nuclear mass [9]. Simultaneously, the technology advance is observed in developments of high current proton accelerators of high energy, in particular the linear ones [10]. As a result, the projects of high-current linacs for average currents up to *100 mA* and proton energy of *1-1.6 GeV* are being developed in some countries [11,12]. On the basis of these accelerators powerful neutron sources are being constructed both for investigations in the neutron physics, and for solution of nuclear power problems.

In this paper a burning process was studied in a subcritical cylindrical reactor driven by an external neutron source with an intensity spherically distributed in space. The reactor blanket was considered to consist of fertile uranium-238 with different plutonium–239 enrichment for which the effective neutron multiplication factor varied in limits of $0\leq K_{ef}<1$.

The calculations are presented for the spatial neutron source generated in the reactor blanket by a proton beam of definite energy, current and radius. However, the general properties of the burning dynamics are valid also for another nature of initial neutrons, in particular, for thermonuclear neutrons in installations of the inertial plasma confinement having the spherical symmetry.

2. BURNING IN A SUBCRITICAL REACTOR WITH EXTERNAL NEUTRON SOURCES

The investigated subcritical reactor is a cylinder of radius R_0 and length $2H_0$. The cylindrical coordinate system (r,z) has been chosen in such a way that the z-axis coincides with a longitudinal cylinder axis, and the system origin is at the cylinder center. The external neutron source intensity $S_0(n/cm^3s)$ is supposed uniformly distributed in a sphere of radius R_{sp} with the center at the coordinate origin. For this geometry the analytical expression may be obtained for the spatial neutron flux density distribution $\Phi(r,z)$ in the reactor [13], solving the diffusion neutron equation in one-group approximation [3,4].

The analysis of neutron field characteristics in the subcritical reactor [13] shows that the absolute value of the neutron flux is $\Phi(r,z)\sim S_0$, and depends essentially on the effective neutron multiplication factor (criticality factor) $K_{ef}=K-(L_D B_{10})^2$, where K is the multiplication factor in an infinite medium and L_D is the neutron diffusion length in the reactor blanket matter, $B_{10}^2=(2.405/R_a)^2+(\pi/2H)^2$. Here $R_a=R_0+0.7\lambda_{tr}$, $H=H_0+0.7\lambda_{tr}$ are respectively extrapolated radius and longitudinal reactor dimension, at which the neutron flux is zero, λ_{tr} is the transport neutron length [3,4]. The case $K_{ef}=0$ corresponds to usual absorption diffuse medium; for $K_{ef}\rightarrow 1$ the flux value $\Phi(r,z)\rightarrow\infty$, i.e. the reactor passes into the critical operation mode and does not need an external neutron source [13].

For numerical calculations of the burning it is necessary to assume the concrete values of external neutron source intensity S_0, and radius R_{sp} of the region occupied by initial neutron source, reactor dimensions R_0 and H_0 and nuclear physical characteristics of the blanket. For the definition of these characteristics in one-group approximation it is necessary to know the neutron energy distribution [3,4].

The neutron energy spectrum was supposed similar to one of the fast reactor with metal uranium-plutonium fuel and a sodium coolant, with the spectral density maximum near *200 keV* [4]. To calculate group constants the energy dependences of microscopic neutron cross sections have been used from several papers, in particular [14].

It was supposed, that the external neutrons are created due to spallation of the blanket material nuclei by protons. In this case $S_0=I\delta_{sp}/r_b^2 l_b e$, where I is the proton beam current, δ_{sp} is the number of neutrons per one proton in medium, e is the proton charge, $R_{sp}=(3r_b^2 l_b/4)^{1/3}$, where l_b is the proton path length in the blanket [13]. Thus, the external source intensity S_0 is proportional to the proton beam current density J. In particular, for $I=1\ mA$, $r_b=5\ cm$ and the proton energy $W=1\ GeV$ we have $S_0=5.9\cdot 10^{13}\ n/cm^3s$, while the neutron flux density $\Phi(r,z)$ at the center of the burning zone varies in the limits of $1.4\cdot 10^{15}\leq\Phi(r,z)\leq 6.5\cdot 10^{15}\ n/cm^3s$ at $0\leq K_{ef}\leq 0.98$, for the reactor dimensions $R_a=40\ cm$, $H=60\ cm$ [13].

The neutron field $\Phi(r,z)$ generated in the subcritical blanket gives rise to the burning process at which the isotope composition of the blanket changes in time as a result of neutron absorption by nuclei and their fission. The neutron radiation captures may be followed by subsequent α- and β-decay of produced isotopes. If the actinide nuclei are fissioned, then about *200 MeV* of energy releases per one fission. If one assumes that the neutron flux $\Phi(r,z)$ is stationary then in the quasilinear approach the variation in time t of density N_i of the i–kind nuclei can be presented as [5]:

$$dN_i(r,z,t)/dt = -\left[\sigma_i^a\Phi(r,z) + \sum_j \lambda_{ij}\right]N_i + \sum_{j\neq i}\left[\sigma_{ji}^c\Phi(r,z) + \lambda_{ji}\right]N_j, \quad (1)$$

where σ_i^a is the microscopic cross section of neutron absorption by a i-nucleus; σ_{ji}^c is the microscopic cross section of neutron radiation capture by a j-nucleus with formation of a i-nucleus; λ_{ij} is the constant of the i-nucleus decay with j-nucleus formation. In the spallation region one needs to take into account the additional nuclide fission by high energy protons, the rate of which is $JN_i\sigma_i^{sp}(W)/e$, where $\sigma_i^{sp}(W)$ is the i-nuclide fission cross section averaged over the path length of protons with the energy W in the blanket.

This paper investigates the temporal dynamics of densities of the main blanket actinides: uranium-238, plutonium and americium isotopes, as well as the total concentration of fission nuclides for the simplified uranium-plutonium fuel cycle [4].

Fig. 1 show variations in the time of densities of ^{238}U, and plutonium isotopes (^{239}Pu, ^{240}Pu, ^{241}Pu), and also the total fission products (FP) at the center of the burning region for the reactor of the concrete dimensions and beam current $I=1\ mA$ ($r_b=5\ cm$). The initial blanket material is fertile ^{238}U ($K_{ef}=0$). As it follows from Fig. 1, ^{238}U density monotonously decreases in time (burning-out), but fissile ^{239}Pu density increases monotonously at the beginning (breeding stage), at $t_m\approx 18$ *years* it reaches the maximum value (equilibrium concentration) and further monotonously decreases. The initial, reduced to the beam current, ^{239}Pu breeding rate for $K_{ef}=0$ is $\sim 2.7\ kg/mA\cdot year$. The equilibrium ^{239}Pu concentration C_m, i.e. $N_{Pu\text{-}239}/N_{U\text{-}238}$, outside the spallation region is defined by corresponding neutron cross sections of absorption and radiation neutron capture:

$$C_m = (N_{Pu\text{-}239}/N_{U\text{-}238})_m=\sigma^c_{U\text{-}238}/\sigma^a_{Pu\text{-}239},$$

as it follows from Eq. (1). For the chosen neutron energy spectrum we have $C_m=0.125$. The time t_m of reaching of equilibrium ^{239}Pu concentration decreases proportionally to the growth of the proton beam current density J.

If the blanket is enriched with fissile ^{239}Pu isotope, the burning dynamics for $0<K_{ef}<1$ depends on the ratio of initial ^{239}Pu concentration in the reactor blanket $C_{Pu\text{-}239}(0)$ to equilibrium one C_m. The time dependences of the main isotope densities in the blanket for $K_{ef}=0.98$, and the extrapolated reactor radius $R_a=40\ cm$ are given in Fig. 2. The needed initial plutonium concentration is $C_{Pu\text{-}239}(0)\approx 0.1$, that is less than the equilibrium one C_m. Corresponding dependences for $R_a=25\ cm$ and $K_{ef}=0.98$ are given in Fig. 3. If $R_a=25\ cm$ then to reach $K_{ef}=0.98$ the initial plutonium enrichment should be $C_{Pu\text{-}239}(0)\approx 0.15$. At $K_{ef}=0.98$ the neutron flux is considerably higher than for $K_{ef}=0$ [13], therefore the burning rates shown in Figs. 2 and 3 are essentially higher than in the case shown in Fig. 1. Since in Fig. 2 $C_{Pu\text{-}239}(0)<C_m$, then for $t<1.5$ *years* one can observe the stage of ^{239}Pu breeding. Correspondingly, in the blanket with high enrichment, Fig. 3, the monotonous burning out of ^{239}Pu takes place.

For this burning mode the maxima of ^{240}Pu and ^{241}Pu isotope densities are reached in ~4 and ~6 years correspondently and further the densities monotonously decrease (transmutation stage), Fig. 3.

Thus, the subcritical blanket in the presence of external neutron sources may be used both for fissile material production, radionuclide transmutation, and power production depending on the isotope composition of the blanket.

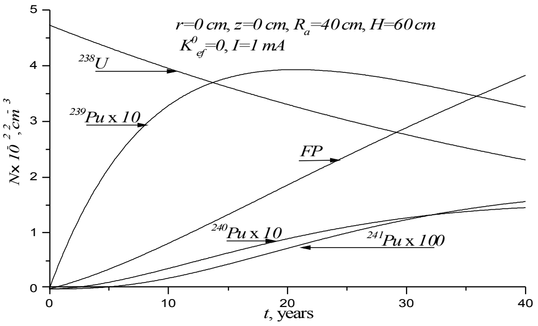

Fig. 1. Time dependences of densities N of uranium–238, plutonium isotopes and fission products (FP) in the burning region center; blanket is fertile uranium - 238

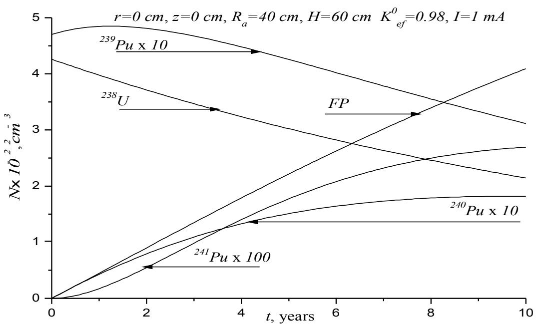

Fig. 2. Time dependences of densities N of uranium–238, plutonium isotopes and fission products (FP) in the burning region center; blanket is fertile uranium – 238 enriched with 10% plutonium-239

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*The work was supported by STCU, project #1480

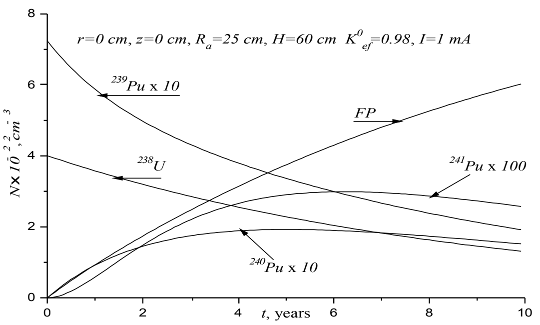

Fig. 3. Time dependences of densities N of uranium–238, plutonium isotopes and fission products (FP) in the burning region center; blanket is fertile uranium – 238 enriched with 15% plutonium-239