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SPHERICAL STANDING BURNING WAVE WITH EXTERNAL AUTOMATIC REACTIVITY CONTROL

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Neutron kinetics of a nuclear burning wave in moving incompressible neutron-multiplying medium in the presence of nuclear reactions is developed. A spherical reactor is considered, where fuel moves with acceleration to the center of the reactor at a velocity $V(r)=V_R(R/r)^2$, and the burning wave travels radially from the center to periphery. The fuel that came to the origin was unloaded from the reactor, and U-238 was loaded to the peripheral area at the same rate. Comparison of theoretical results with computer simulation using MCNPX code was performed.

INTRODUCTION

In this article, the theory of nuclear reactor on spherical standing burning wave is developed. The neutron kinetics of a nuclear burning wave in a moving neutron-multiplying medium in the presence of nuclear reactions was developed. Computer simulation of moving and standing spherical burning waves in a nuclear reactor was performed using MCNPX code [1].

The reactor core consists of four areas: the outer zone made of U-238, the breading zone where production of Pu-239 takes place according to the scheme U-238 + n = U-239 → Np-239 → Pu-239, the inner region in which Pu-239 is burning, and central area consists of burnt fuel. The fuel moves with acceleration from periphery to the center of the reactor. It is shown that in such a system a spherical standing wave travels radially from the center zone to periphery. The burning wave consists of two regions: the external – breading zone and the internal – burning area. Distributions of the neutron flux, the U-238, Np-239, and Pu-239 isotope concentrations and the specific power in the standing spherical burning wave are obtained in this paper. The conditions for existence of spherical standing burning waves are investigated. It is shown that an operation mode of the standing-wave reactor is characterized by two combinations of nuclear cross sections and single function defining the stability boundaries of the stem. Stability region of spherical waves was found to be broader then stability region of one-dimensional traveling burning waves in an infinite medium. A state diagram of such a reactor has been obtained.

Concept of the traveling wave nuclear reactor (TWR) is one of the brilliant ideas of 20-th century. It suggests using depleted uranium (or thorium) as fuel and promises to supply inexhaustible source of energy worldwide. This idea was proposed by S.M. Feinberg, realized in theory by L.P. Feoktistov [2] and developed in many publications (see bibliography in [3]), in which several ways of its practical implementation were suggested. One of the most promising designs of TWR is a fast reactor, which is able to work in maneuverable mode [3, 6]. Mathematical modeling of TWR using MCNPX code was performed in [4, 7, 8].

Computer simulation of reactor on standing and traveling spherical burning wave has been carried out in present article. The computer model of the reactor using the MCNPX code is a ball of 2 m radius filled with uranium dioxide fuel. In the traveling spherical wave mode, nuclear burning begins in the central zone of the core enriched with uranium. When concentration of Pu-239 in U-238 becomes high enough due to breeding mechanism according to the scheme U-238 + n = U-239 → Np-239 → Pu-239, a spherical burning wave appears; then it breaks away from the ignition region and continuously moves to the edges of the core during ~ 150 years. In our model at a power of 240 MW, the burning wave velocity was 0.5 cm/year. The mode of a standing spherical burning wave (SWR) was achieved by selecting the values of fuel speed and reactor power. Radial distributions of neutron flux, power density and the concentrations of Pu-239 and U-238 in the spherical standing burning wave were obtained using MCNPX code. A comparison of theoretical results with the data of numerical simulation has been carried out. Possibility of using depleted uranium as a nuclear fuel in reactors on spherical burning wave is confirmed.

1. NEUTRON KINETICS EQUATION IN MOVING NEUTRON-MULTIPLYING MEDIUM

Let us consider nuclear burning wave in incompressible uranium-based medium, which moves to the center of the reactor at velocity $V(r) = V_R(R/r)^2$, where V_R is speed of fuel at periphery of the reactor at r = R.

The simplest description of neutron kinetics and burning of nuclear fuel can be obtained using the coordinate system x ', y ', z ', in which the fuel is stationary:

$$\frac{1}{\mathrm{v}}\frac{\partial\Psi}{\partial t} = \hat{D}\Psi + (\nu\Sigma_f - \Sigma_a)\Psi + S\,; \qquad (1)$$

$$\frac{\partial n_8}{\partial t} = -n_8\sigma_{a8}\Psi\,, \qquad \frac{\partial \tilde{n}_9}{\partial t} = \sigma_{89}\, n_8\Psi - \frac{\tilde{n}_9}{\tau_{89}}\,,$$

$$\frac{\partial n_9}{\partial t} = \frac{\tilde{n}_9}{\tau_{89}} - \sigma_{a9}\, n_9\Psi\,,\ \frac{\partial n_c}{\partial t} = 2\sigma_{f9} n_9\Psi\,, \qquad (2)$$

where $\Psi(\vec{r}',t)$ is neutron flow; v is speed of neutrons; $n_8(\vec{r}',t)$ is concentration of ^{238}U; $\tilde{n}_9(\vec{r}',t)$ is concentration of ^{239}Np; $n_9(\vec{r}',t)$ is concentration of ^{239}Pu; $n_c(\vec{r}',t)$ is concentration of fission products; $\hat{D}$ – neutron transport operator; $\Sigma_f = \sigma_{f9} n_9$ – macroscopic cross-section of fission and $\Sigma_a = \sigma_{a8} n_8 + \sigma_{a9} n_9 + \sigma_c n_c$ – macroscopic neutron absorption cross section. S – term describing the reactor operating controls; σ_{89} – transmutation cross-section of ^{238}U to ^{239}Pu; τ_{89} – time of the decay in chain $^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$; σ_{f9} – fission cross-section of ^{239}Pu; ν – the number of fission neutrons; σ_{a8} and σ_{a9} – neutron absorption cross-sections for nuclei ^{238}U and ^{239}Pu; σ_c is neutron absorption cross-section for fission products. To simplify we put $\sigma_{a8} = \sigma_{a9} = \sigma_a$.

Boundary conditions have to be added to Eqs. (1) and (2):

$$\Psi(\infty, t) = 0,\ \Psi'(0, t) = 0,\ n_9(\infty, t) = 0,$$

$$\tilde{n}_9(\infty, t) = 0,\ n_c(\infty, t) = 0,\ n_8(\infty, t) = n_8(0). \quad (3)$$

We need to find a time-independent solution of equations (1) in the form of a spherical standing wave $\Psi(r)$, $n_8(r)$, $n_9(r)$. Consider the movement of fuel materials rather slow: $\tau_{89} V << L$, where L is the characteristic size of the burning region, then Eqs. (1), (2) can be interpreted as quasi-stationary (v=∞). The operator $\hat{D}$ we choose in diffusion approximation.

The boundary conditions (3) look as follows:

$$\Psi(\infty) = 0,\ \Psi'(0) = 0,\ n_9(\infty) = 0,$$

$$n_c(\infty) = 0,\ n_8(\infty) = n_0. \quad (4)$$

2. THEORY OF SPHERICAL NUCLEAR BURNING WAVE

Equation for fluence

Now, instead of the r coordinate we will introduce a new variable

$$\varphi(r) = \sigma_a \int_r^\infty \frac{\Psi(r')}{V(r')} dr' = \frac{\sigma_a}{V_R R^2} \int_r^\infty \Psi(r') r'^2\, dr',$$

which is proportional to fluence $F(x)$ and ranges from 0 to a maximum value of $\varphi_0 = \sigma_a F_{\max}$. Let us choose the function $S(x)$ describing the automatic control on excess reactivity ρ as: $S = -\rho \nu \Sigma_f \Psi$. After these changes Eqs. (1) and (2) become:

$$\frac{D\sigma_a^2}{2V_R^2 R^4} \frac{\partial}{\partial \varphi}\left(r^4 \frac{\partial \Psi^2}{\partial \varphi} \right) + \nu(1-\rho)\Sigma_f - \Sigma_a = 0, \quad (5)$$

$$\frac{dn_8}{d\varphi} = -n_8, \quad (6)$$

$$\frac{dn_9}{d\varphi} = n_8 \sigma_{89} / \sigma_a - n_9, \quad (7)$$

$$\frac{dn_c}{d\varphi} = 2n_9 \sigma_f / \sigma_a, \quad (8)$$

$$P = 4\pi V_R Q R^2 / \sigma_a \int \Sigma_f\, d\varphi, \quad (9)$$

$$\Sigma_f = \sigma_f n_9, \quad (10)$$

$$\Sigma_a = \sigma_a (n_8 + n_9) + \sigma_c n_c, \quad (11)$$

where Q is nuclei ^{239}Pu fission energy release.

The boundary conditions (4) for the functions $\Psi(\varphi)$, $n_8(\varphi)$, $\tilde{n}_9(\varphi)$, $n_9(\varphi)$ look as follows:

$$\Psi(0) = 0; \Psi'(\varphi_0) = 0; n_9(0) = 0; n_c(0) = 0; n_8(0) = n_0, \quad (12)$$

where $\varphi_0 = \varphi(0)$ is the maximum neutron fluence.

Equation for neutron flux density

Equations (6) - (8) can be solved:

$$n_8(\varphi) = n_0 e^{-\varphi},\ n_9(\varphi) = \sigma_{89} / \sigma_a n_0 \varphi e^{-\varphi},$$

$$n_c(\varphi) = 2\sigma_f \sigma_{89} / \sigma_a^2 n_0 [1 - (1+\varphi) e^{-\varphi}], \quad (13)$$

where n_0 is concentration of U-238 in the initial material, and equation (5) becomes:

$$\frac{D\sigma_a}{2n_0 V_R^2} \frac{d}{d\varphi}\left(\frac{r^4(\varphi)}{R^4} \frac{d\Psi^2}{d\varphi} \right) = 2\beta + (1-2\beta) e^{-\varphi} + \left(\frac{\sigma_{89}}{\sigma_a} - 2\beta \right) \varphi e^{-\varphi} - \frac{\sigma_f \sigma_{89}}{\sigma_a^2} \nu (1-\rho) \varphi e^{-\varphi}, \quad (14)$$

where $\beta = \sigma_c \sigma_f \sigma_{89} / \sigma_a^3$ is a parameter, which determines the speed of breeding in the system.

System excess reactivity calculation

Integrating equation (14) over φ taking into account the boundary condition $\Psi(0) = 0$, we obtain:

$$\frac{D\sigma_a}{2n_0 V_R^2} \frac{r^4(\varphi)}{R^4} \frac{d\Psi^2}{d\varphi} = f(\varphi), \quad (15)$$

where

$$f(\varphi) = 2\beta\varphi - (1-2\beta)(e^{-\varphi} - 1) + \left[\frac{\sigma_{89}}{\sigma_a} - 2\beta - \frac{\sigma_f \sigma_{89}}{\sigma_a^2} \nu (1-\rho) \right] [1 - (1+\varphi) e^{-\varphi}].$$

Substituting $\varphi = \varphi_0$ in (15) and using the boundary conditions (12), we obtain the equation for the system excess reactivity ρ:

$$f(\varphi_0) = 0. \quad (16)$$

Solving Eq. (16) we obtain expression for excess reactivity, which is necessary for the existence of a stationary solution:

$$\rho = \frac{\sigma_a^2}{\sigma_f \sigma_{89} \nu} (c - q_0) \quad (17)$$

where

$$q_0 = \frac{2\beta\varphi_0 - (1-2\beta)(e^{-\varphi_0}-1)}{1-(1+\varphi_0)e^{-\varphi_0}}, \text{ and}$$

$$c = \left(\nu\frac{\sigma_f}{\sigma_a} - 1\right)\frac{\sigma_{89}}{\sigma_a} + 2\beta. \qquad (18)$$

Eq. (17) and (18) relate excess reactivity ρ to the maximum fluence in unloaded fuel φ_0. This value lies in the range $0 \le \varphi_0 \le \chi$, where χ is the maximum fluence in the flat burning wave [4] (Eq. (19) and Fig. 1):

$$\beta = \frac{(e^{-\chi}-1)^2 - \chi^2 e^{-\chi}}{\chi^2[(1+\chi)e^{-\chi}-1] + 2(\chi + e^{-\chi} - 1)^2}. \qquad (19)$$

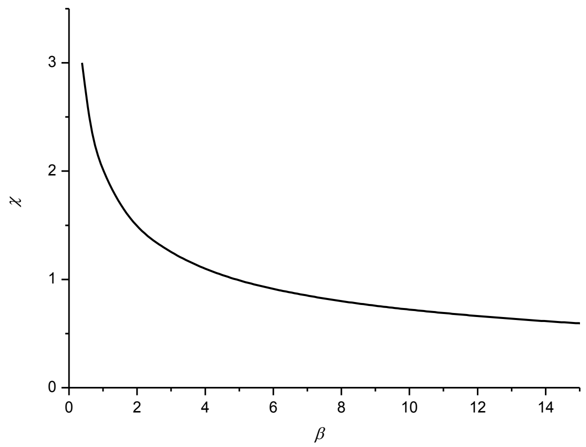

Fig. 1. Dependence $\chi(\beta)$

Neutron field calculation

Substituting (17) to (15) we obtain:

$$\frac{D\sigma_a}{2n_0 V_R^2}\frac{r^4(\varphi)}{R^4}\frac{d\Psi^2}{d\varphi} = f_1(\varphi, q_0), \qquad (20)$$

where $f_1(\varphi, q_0) = 2\beta\varphi - (1-2\beta-q_0)(e^{-\varphi}-1) + q_0\varphi e^{-\varphi}$.

The function $f_1(\varphi, q_0)$ has the following analytical properties [7, 8]: $f_1(0, q_0) = 0$, $f_1(\varphi_0, q_0) = 0$; it becomes zero at the ends of the range $0 \le \varphi \le \varphi_0$.

Substituting expression $\Psi = -\frac{V_R}{\sigma_a}\left(\frac{R}{r}\right)^2\frac{d\varphi}{dr}$ in equation (20) and introducing new dimensionless variables $\psi = \frac{D}{n_0 V_R R}\sqrt{\frac{D}{n_0\sigma_a R^2}}\Psi$;

$\zeta = \sqrt{(n_0\sigma_a)/D}\, r$,

we get the system of equations:

$$\frac{d\psi}{d\zeta} = -f_1(\varphi)/\zeta^2, \qquad (21)$$

$$\frac{d\varphi}{d\zeta} = -\psi\zeta^2 \qquad (22)$$

with boundary conditions

$$\varphi(\infty) = 0,\ \varphi(0) = \varphi_0,\ \psi(\infty) = 0. \qquad (23)$$

Set φ_0 in the interval $0 < \varphi_0 < \chi$ and solve equations (21), (22) with boundary conditions (23) by the shooting method: choose a value ψ_0 and start from $\zeta = 0$ with initial conditions $\varphi(0) = \varphi_0$ and $\psi(0) = \psi_0$; we obtain solutions $\varphi(\zeta)$ and $\psi(\zeta)$ diverging at $\zeta \to \infty$. We select ψ_0 so that the region of divergence was as far as possible.

Returning to the variables r, $\varphi(r)$, and $\Psi(r)$, we find the radial dependences of the neutron fluence $\varphi(r)$, and flux $\Psi(r)$, as well as the concentration profiles of plutonium

$$n_9(r) = \sigma_{89}/\sigma_a n_0\ \varphi(r)\, e^{-\varphi(r)}, \qquad (24)$$

uranium $n_8(r) = n_0 e^{-\varphi(r)}$ and fission products

$$n_c(r) = 2\sigma_f\sigma_{89}/\sigma_a^2 n_0[1-(1+\varphi(r))e^{-\varphi(r)}]. \qquad (25)$$

We also get the expression for power:

$$P = \int Q\Sigma_f \Psi dV =$$

$$= 4\pi Q V_R R^2 n_0 \sigma_{89}\sigma_f/\sigma_a^2[1-(1+\varphi_0)e^{-\varphi_0}]. \qquad (26)$$

The speed of fuel movement is proportional to the power of the reactor. The burning wave profile remains unchanged.

The main result of theory is that spherical standing-burning wave can be described with tree parameters: two combinations of nuclear cross sections c, β and neutron fluence φ_0 in unloaded fuel.

Fig. 2 shows an example for radial profiles of the neutron flux in standing burning waves for material parameter $\beta = 1$ (when $\chi = 2$ – the maximal value of φ_0) and different values of the parameter φ_0.

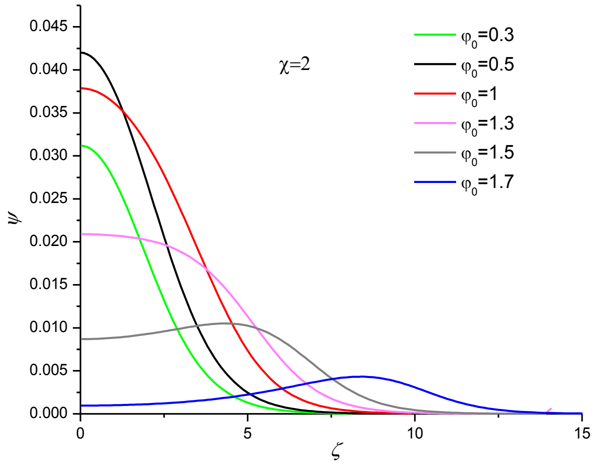

Fig. 2. Radial dependences of the neutron flux $\psi(\zeta)$ in standing waves, $\chi = 2$

The maximum of neutron flux in the burning wave (see Fig. 2) moves away from the center of the core when φ_0 increases and goes to infinity at $\varphi_0 = \chi$.

Fig. 3 shows dependence the power of the standing burning wave on the fluence φ_0 at $\chi = 1$. The fundamental difference between a spherical standing-wave reactor and a one-dimension traveling-wave reactor is that its power can be physically limited by choosing a sufficiently small parameter φ_0 and small dimensions of the core. Spherical standing-wave differs from a traveling burning wave Feoktistov's type, in which the power and neutron fluxes are much more than modern structural materials can allow.

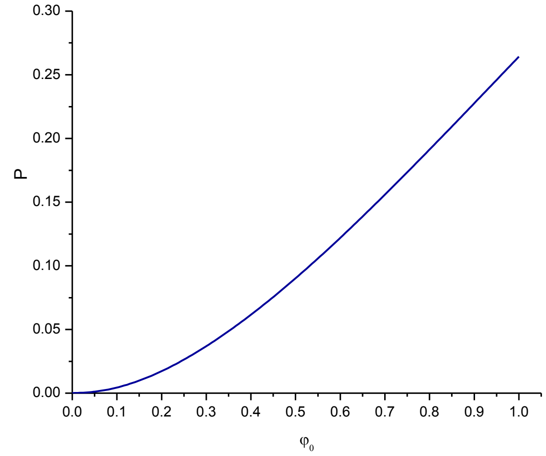

Fig. 3. Dependence of power of the standing burning wave on the fluence φ_0 with $\chi = 1$

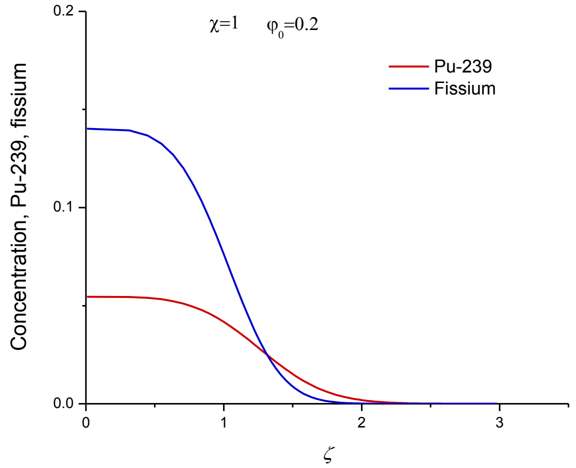

Fig. 4. Dependences of Pu-239 concentrations and fission products on the radius

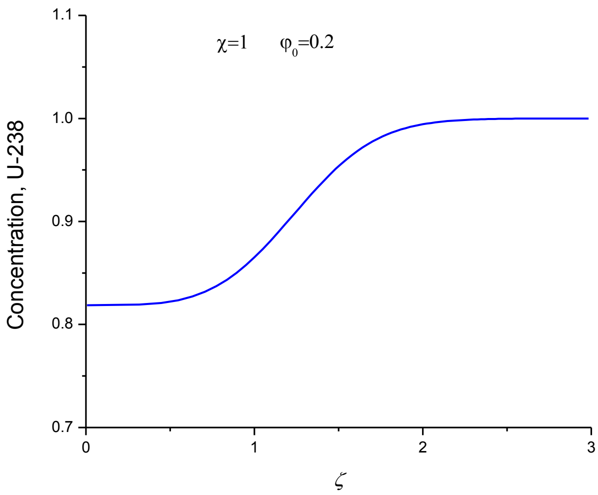

Fig. 5. Dependence of U-238 concentration on the radius in the standing burning wave

Figs. 4,5 show the dependences of the concentrations of Pu-239, U-238 and fission products on the radius in the standing burning wave of a spherical shape. From Fig. 5 one can see that in the standing burning wave with the specified parameters, the uranium isotope U-238 burns out by 18%, and in the spent fuel there are still ~ 6% Pu-239.

3. ANALYSIS OF STABILITY THE SPHERICAL BURNING WAVE

In Fig. 6 the family of phase trajectories $\psi(\varphi)$ for different values of φ_0 is shown.

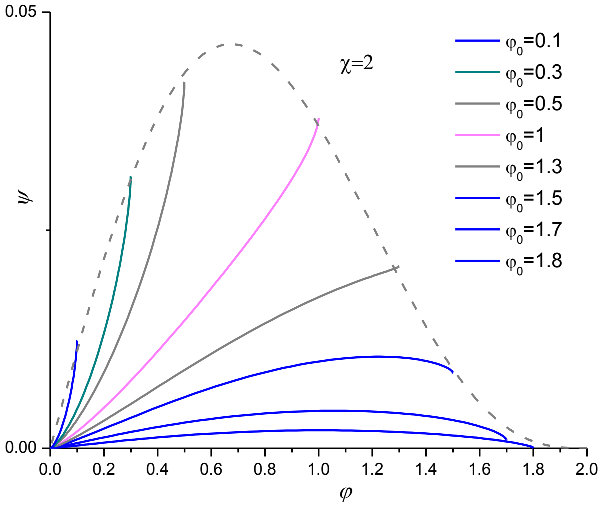

Fig. 6. Dependence $\psi(\varphi)$ for a some values of φ_0 at $\chi = 2$

A necessary condition for stability of a standing burning wave is the positivity of the values of φ and ψ along the trajectory of the solution $\varphi(\zeta)$ and $\psi(\zeta)$. Thus, the entire trajectory of the dependence $\varphi(\psi)$ should lie in the first quadrant. As can be seen in Fig. 6 this condition is valid.

Calculation of the minimum value of the parameter with the scope of the solution

The condition $\rho \geq 0$ for the existence of a standing spherical wave gives a relation:

$$c \geq q_0(\beta, \varphi_0). \qquad (27)$$

Relation (27) determines $c_{\min}(\varphi_0)$ – the minimum value of c, for which a stationary solution still exists for a given value of φ_0. The dependence $c_{\min}(\varphi_0)$ has the form:

$$c_{\min}(\varphi_0, \beta) = \frac{2\beta\varphi_0 - (1-2\beta)(e^{-\varphi_0} - 1)}{1-(1+\varphi_0)e^{-\varphi_0}}. \qquad (28)$$

The dependence $c_{\min}(\varphi_0, \beta)$ calculated using (28) for the value $\beta = 1$ is shown in Fig. 7. The wave exists in the open region of the graph. The dependence $c_{\min}(\varphi_0, \beta)$ has a minimum, indicated in the graph as $c_{mm}(\beta)$, which is located below the line $q(\beta)$ corresponding to a plane burning wave. One can see from Fig. 7 that a standing spherical burning wave is more stable than a plane burning wave, and two times lower fluency φ_0 is required for existence of a standing wave.

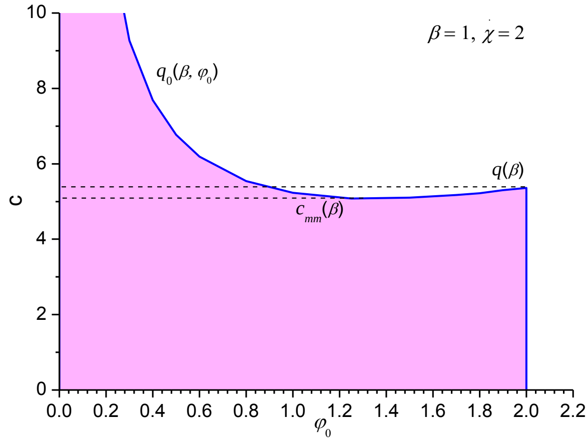

Fig. 7. Dependence of $c_{\min}(\varphi_0, \beta)$ on φ_0 with β=1,(χ= 2)

State diagram of a reactor on the standing spherical burning wave

The dependence of $c_{mm}(\beta)$ is shown in Fig. 8 with dotted line. It represents the lower limit of parameter c for standing burning wave stability in a spherical reactor. For comparison, the lower limit of c for a plane burning wave stability in an infinite medium $q(\beta)$ [4] is shown in the same graph.

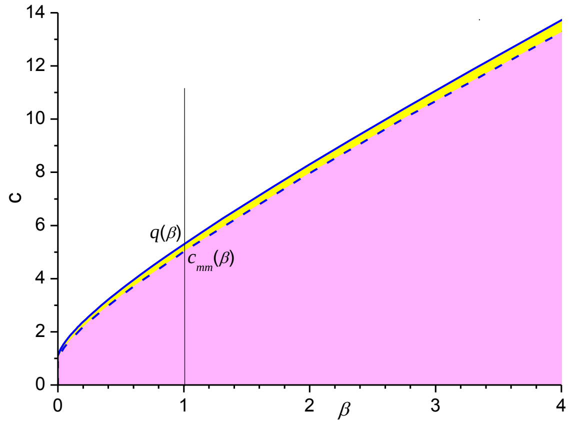

Fig. 8. State diagram of the reactor on a standing spherical burning wave

The state diagram of a reactor on a standing spherical burning wave is shown in Fig. 8. In the pink shaded region there are no standing waves, in the region shaded in yellow the spherical standing waves exist only for some values of φ_0. In the open region of the Fig. 8 the waves exist for any values of φ_0.

4. COMPUTER SIMULATION OF SPHERICAL TRAVELLING BURNING WAVE

Computer model of STBW is a sphere with radius R =2 m, filled with uranium dioxide based fuel, which is divided into spherical layers with thickness of 5 cm. In order to reach criticality an igniter containing enriched uranium was located in the central part of the reactor core. Due to transmutation under fast neutron irradiation the ^{238}U isotope converts to ^{239}Pu according to the chain: $^{238}U + n = {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$. When concentration of ^{239}Pu in the fuel reaches high level, spherical burning wave appears; it breaks away from the central area and moves to the edges of the active zone during 30 years. In this model the speed of the burning wave is ~0.5 cm/year at 240 MW power (see Figs. 9 and 10 in which radial distributions of neutron flux and power are shown).

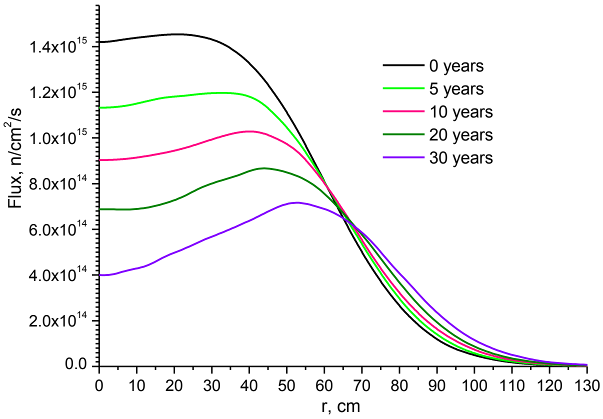

Fig. 9. Radial dependences of the neutron flux density in a traveling spherical burning wave for period of 30 years

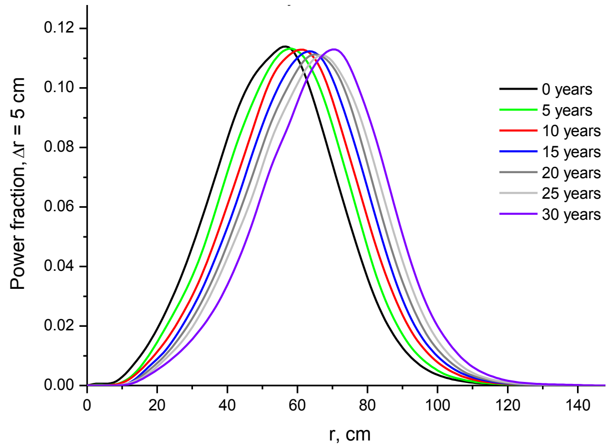

Fig. 10. Radial distribution of power fraction of the layers in the traveling spherical burning wave during 30 years at 240 MW power

5. COMPUTER SIMULATION OF SPHERICAL STANDING BURNING WAVE

In SWR model fuel is moving towards the burning wave at the same speed, that ensures the stationarity of breading and burning processes in the reactor. The results of computer simulation of a standing nuclear burning wave during 20 years are shown in Fig. 11. It shows that parameters of the model ensure stationary of the spherical nuclear burning wave when reactor is fed with depleted uranium. Figs. 11–13 show dependences of power density and concentrations of Pu-239 and U-238 on the radius, which were obtained using MCNPX computer simulation of the spherical standing burning wave. They are in qualitative agreement with the theoretical results (see Figs. 3–5).

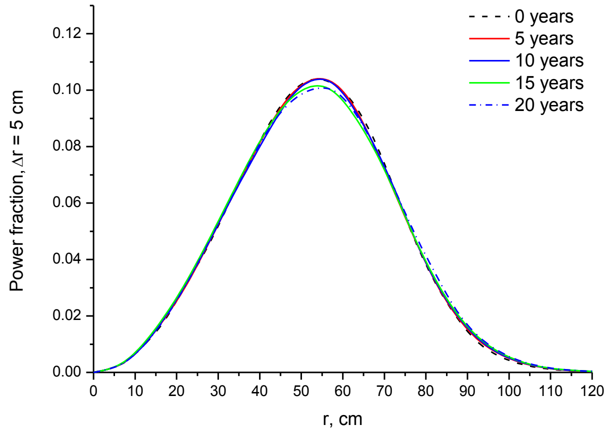

Fig. 11. Radial distribution of power fraction of the layers in a standing spherical burning wave over a period of 20 years

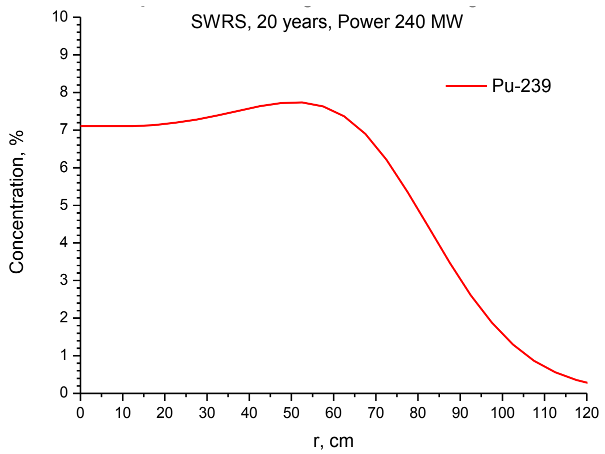

Fig. 12. Dependence of Pu-239 concentration on the radius in the standing burning wave

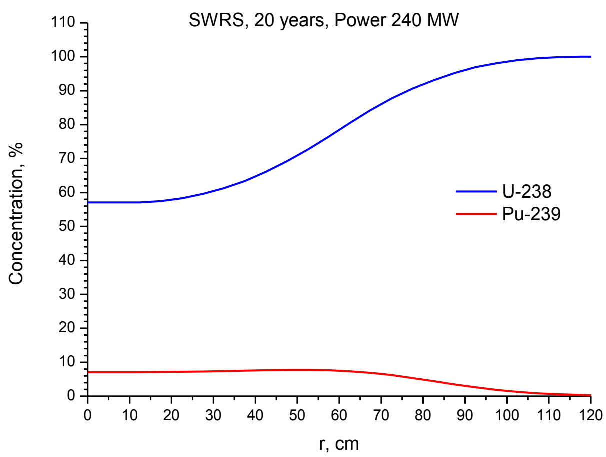

Fig. 13. Dependence of the concentrations of U-238 and Pu-239 on the radius in the standing burning wave

CONCLUSION

• Standing nuclear burning wave can exist not only in one-dimensional geometry, but in systems with cylindrical and spherical symmetries as well.

• Phenomenological theory of standing spherical nuclear burning wave was developed

• Existence of a standing spherical nuclear burning wave was proved for a reactor with fuel continuously moving toward the center.

• State diagram of such a reactor was proposed and the boundaries of the standing wave existence were defined.

• Mathematical modeling of reactor on spherical standing burning wave was carried out using MCNPX code, and obtained numerical results are in agreement with results of the phenomenological theory.

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СФЕРИЧЕСКАЯ СТОЯЧАЯ ВОЛНА ЯДЕРНОГО ГОРЕНИЯ С ВНЕШНИМ АВТОМАТИЧЕСКИМ КОНТРОЛЕМ РЕАКТИВНОСТИ

Ю.Я. Лелеко, В.В. Ганн, А.В. Ганн

Была развита нейтронная кинетика стоячей волны ядерного горения в нейтронно-размножающей среде, которая не сжимается и является подвижной, при наличии ядерных реакций. Рассмотрен сферический реактор, в котором волна ядерного горения движется радиально от центра, а топливо – в центр реактора. Показано, что при подпитке такой системы ^{238}U в ней может существовать сферическая стоячая волна ядерного горения. Проведено сравнение теоретических результатов с данными численного моделирования такого реактора с использованием кода MCNPX.

СФЕРИЧНА СТОЯЧА ХВИЛЯ ЯДЕРНОГО ГОРІННЯ З ЗОВНІШНІМ АВТОМАТИЧНИМ КОНТРОЛЕМ РЕАКТИВНОСТІ

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Була розвинена нейтронна кінетика стоячої хвилі ядерного горіння в нейтронно-розмножуючім середовищі, котре не стискається та є рухомим, при наявності ядерних реакцій. Розглянуто сферичний реактор, в якому хвиля ядерного горіння рухається радіально від центра, а паливо – до центра реактора. Показано, що при підживленні такої системи ^{238}U в ній може існувати сферична стояча хвиля ядерного горіння. Проведено порівняння теоретичних результатів з даними чисельного моделювання такого реактора з використанням коду MCNPX.