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SIMULATION OF THE FEOKTISTOV TRAVELING WAVE OF NUCLEAR BURNING IN URANIUM WITH THE MCNPX CODE

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A mathematical simulation of the Feoktistov traveling wave of nuclear burning in depleted uranium was performed using the Monte Carlo method using the MCNPX code supplemented with reactivity feedback in order to find the value of the steady-state power of the system. The obtained values of velocity V = 2.8 cm/day and the reduced power of the traveling wave of burning p = 35 MW/cm^2.

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INTRODUCTION

A traveling burning wave reactor (BWR) is a promising tool for solving nuclear energy problems. It can use depleted uranium or even spent fuel from thermal nuclear reactors as nuclear fuel. This promises to provide humanity with an inexhaustible source of nuclear energy. The idea of BWR, expressed by S.M. Feinberg, received a theoretical description in the work of L.P. Feoktistov [1] and was developed in publications by E. Teller [2], Van Dam [3], H. Sekimoto [4] and N.F. Shulga with co-workers [5]. Two types of BWR reactors are known: Feoktistov's self-regulating nuclear burning wave – a reactor with a fixed power and Teller's reactor with external negative feedback on reactivity, which can operate in a maneuverable load tracking mode [2, 6]. Computer modeling of a controlled BWR using the MCNPX Monte Carlo code was performed in [7].

In this paper, a modeling of the Feoktistov self-regulating reactor was performed using the Monte Carlo method. The problem is that the power of such a reactor is not known in advance, and the MCNPX program requires specifying the power of the system. To solve this problem, a calculation model was created that would allow calculating the steady-state value of the Feoktistov BWR power.

1. MODEL DESCRIPTION

A rod with a radius of 30 cm and a length of 300 cm made of ^{238}U was modeled, divided by planes into layers with a thickness of Δx = 5 cm. Mirror boundary conditions were set at the left end and on the side surface of the rod. The left 4 layers contained enriched uranium with 50% ^{235}U, the remaining layers contained only depleted uranium ^{238}U. The MCNPX code was used to simulate the burning processes in enriched uranium layers and the production of ^{239}Pu from ^{238}U. When the concentration of ^{239}Pu in ^{238}U becomes high enough due to its production according to the scheme $^{238}U + n = {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$, then a traveling wave of nuclear burning appears near the left edge of the rod, it breaks away from the ignition region and continues to move along the rod (see Fig. 1). The value of the system power was selected that would ensure the achievement of a mode with k_{eff} ~ 1 at the end of the ignition phase. Fig. 1 shows the power distribution by layers during the ignition of the traveling wave of burning. The process of plutonium production in the burning wave is determined by the chain of transformations:

$$^{238}U(n,\gamma)\rightarrow {}^{239}U(\beta^-)\xrightarrow{23.5min} {}^{239}Np(\beta^-)\xrightarrow{2.3day} {}^{239}Pu(n,fis).$$

Plutonium production lags by 2.3 days behind the moment of neutron capture by the ^{238}U nucleus, and the wave power is proportional to its speed. With a random increase in the wave power, the production profile begins to lag behind the burnup profile, which leads to a decrease in the ^{239}Pu concentration in the burning zone and to a decrease in k_{eff}. As a result, the power decreases to a stationary value. Thus, self-regulation of reactivity is automatically performed in the Feoktistov wave.

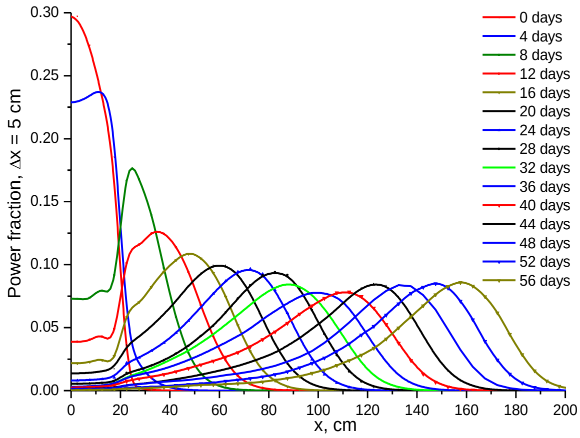

Fig. 1. Simulation of the ignition process of a traveling wave

Based on the MCNPX code, a software package was developed that simulates a traveling wave of nuclear burning using the Monte Carlo method. Since the MCNPX program models nuclear burning processes only at a given power in the system P, the complex had to be supplemented with a program providing negative feedback on k_{eff}, which would select the value of the system power P in such a way as to ensure that the system state with k_{eff} = 1 is achieved and maintained.

A program was written that reads the values of k_{eff} and the concentration of isotopes in the fuel layers from the output file of the previous cycle, determines the new value of the system power P using the formula: $P = P_0 + \alpha (k_{eff} - 1)$, (where α is the feedback coefficient), compiles the text of the input file for the next MCNPX cycle, launches and maintains the MCNPX program. The reboot cycle ΔT = 3 days was divided into 3 parts, so that the time step of the program 1 day became less than the half-life of ^{239}Np equal to 2.3 days.

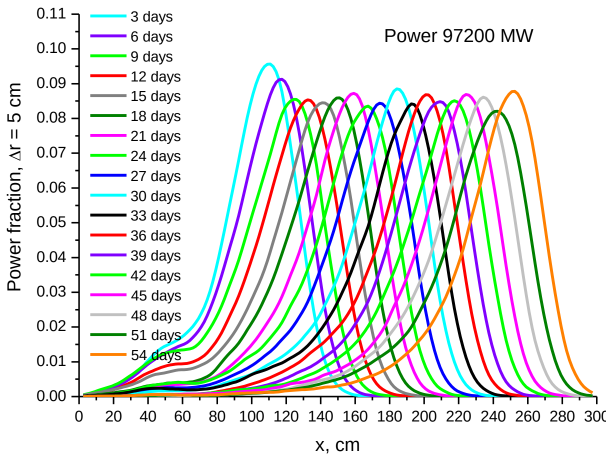

Fig. 2. Motion of traveling nuclear burning wave

2. SIMULATION RESULTS

Figs. 2-5 show the calculation results for the traveling wave of nuclear burning with an interval between overloads of ΔT = 3 days (see Fig. 2), with an initial power of 62 000 MW, which after 33 days reached a steady-state value of 97 200 MW (see Fig. 3). The dynamics of k_{eff} reaching a steady-state value with k_{eff} = 1 is shown in Fig. 3. In this case, the reduced wave power was p = 35 MW/cm2, and the traveling wave velocity was V = 2.8 cm/day. It should be emphasized that the slowness of the U –> Pu burning process is ensured by the long half-life of ^{239}Np equal to 2.3 days.

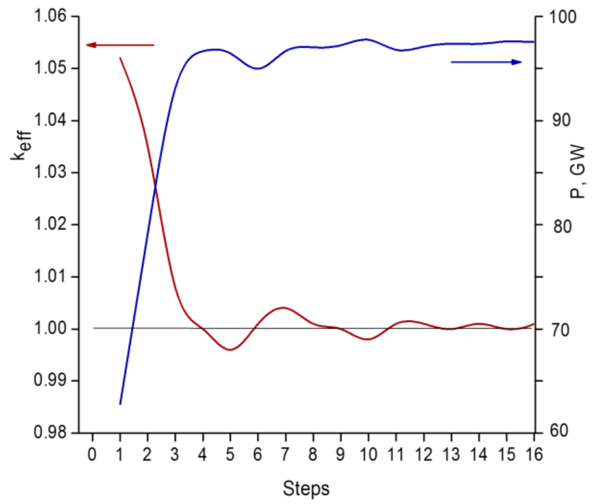

Fig. 3. Dynamics of k_{eff} change and wave power P in the process of searching for a state with k_{eff}=1

The concentration profile of ^{238}U is shown in Fig. 4, the burn up degree is 81%.

Profiles of Np and Pu concentrations are shown in Fig. 5. In the wave front region, the isotope ^{239}Pu accumulates due to the transformation chain (1), and in the center of the wave, the isotope ^{239}Pu partially burns out due to fission processes or its transformation into isotopes ^{240}Pu and ^{241}Pu. As a result, the concentration of ^{239}Pu in the burnt fuel is 1.4%.

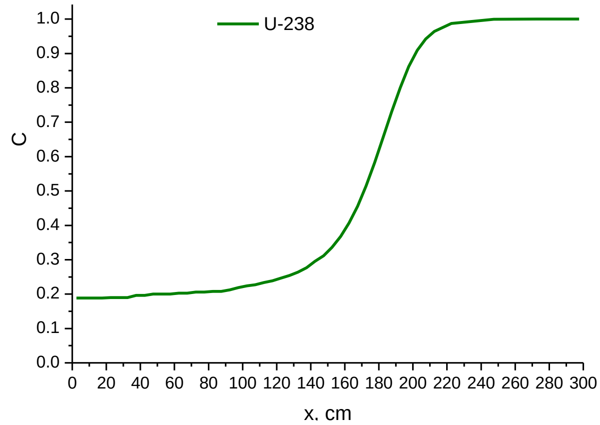

Fig. 4. Profile of ^{238}U concentration

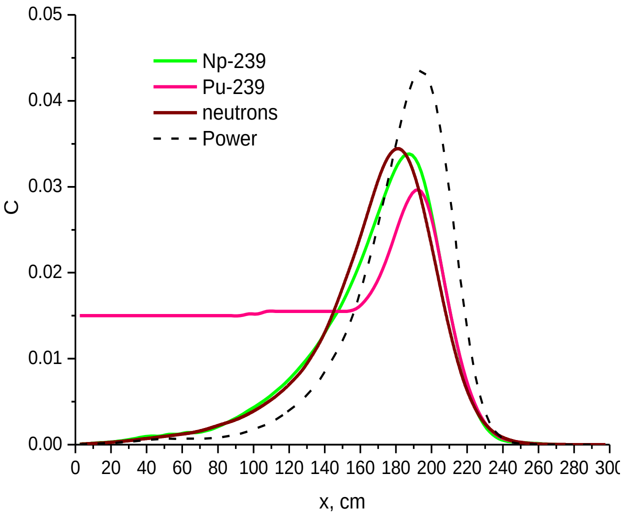

Fig. 5. Profiles of Np and Pu isotope concentrations, neutron flux density and power

Table presents the main parameters of the traveling nuclear burning wave obtained from the simulation results using the MCNPX program.

Parameters of traveling wave

Velocity of wave	2.8 cm/day
Relative power	35 MW/cm^2
Specific power	1.2 GW/cm^3
^{239}Pu concentration, max.	3 at.%
Neutrons flow dens., max.	2.5·10^{18} n/cm^2/c
^{238}U utilization coefficient	81%
^{239}Pu % in corium	1.4 at.%

3. COMPARISON OF SIMULATION RESULTS WITH ANALYTICAL RESULTS

A comparison of the simulation results shown in Figs. 4 and 5 was carried out with the analytical results of work [8]. Figs. 6-9 presents the results of comparison of isotope concentrations depending on the dimensionless coordinate $\zeta=(x-Vt)/l$, where l is the neutron diffusion length.

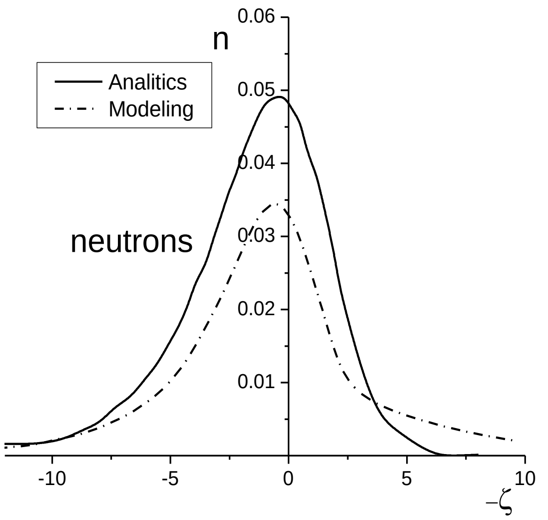

Fig. 6. Neutron concentration profiles in the wave, calculated analytically [8] and obtained by modeling

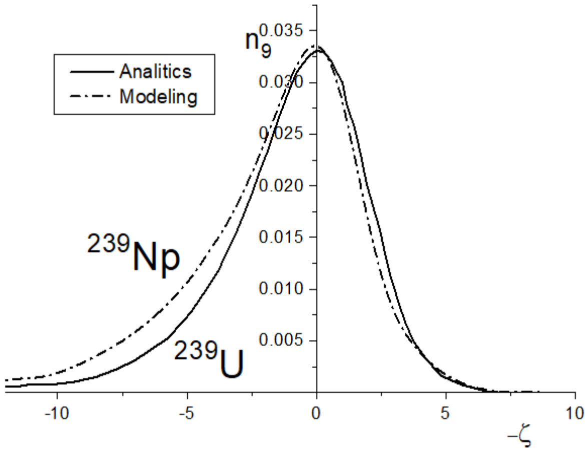

Fig. 7. ^{239}Np concentration profile obtained by modeling in comparison with the concentration of the ^{239}U isotope calculated analytically [8]

We compare the concentration of the ^{239}Np isotope calculated by us with the concentration of the ^{239}U isotope obtained in [8] because the intermediate isotope ^{239}Np was not considered in [8], and the isotope ^{239}U was directly converted into ^{239}Pu with a half-life of 2.4 days.

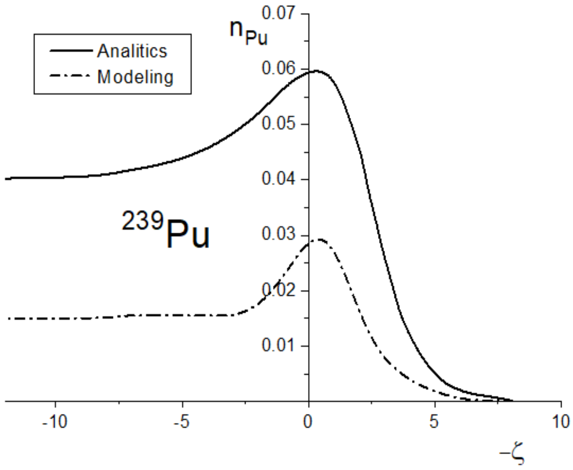

Fig. 8. Comparison of ^{239}Pu concentration profiles calculated analytically [8] and obtained by modeling

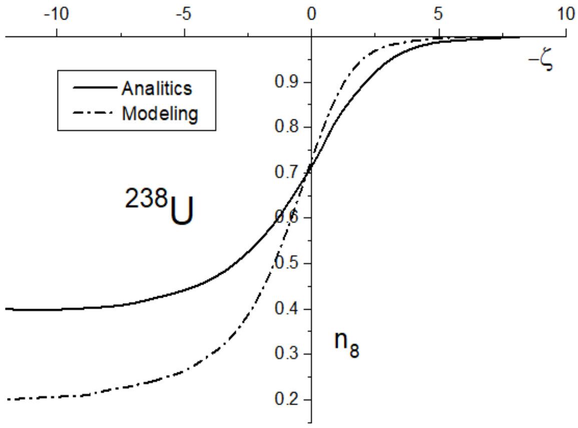

Fig. 9. ^{238}U concentration profiles calculated analytically [8] and by modeling

As can be seen from Figs. 6-9, the modeling results are in satisfactory agreement with the analytical results. The large difference in the ^{239}Pu concentrations in the burned-up fuel (see Fig. 8) is due to the fact that a significant portion of the ^{239}Pu isotopes, absorbing neutrons, are converted into ^{240}Pu and ^{241}Pu isotopes, avoiding the fission process, and these reaction channels were not considered in [8]. This also explains some difference in the burn up degree of ^{238}U (see Fig. 9).

4. DISCUSSION

By mathematically modeling the traveling wave of nuclear burning in uranium by the Monte Carlo method using the MCNPX program, the following values of the Feoktistov wave parameters were obtained (see Table): wave velocity V = 2.8 cm/day, power released from a unit area of the wave p = 35 MW/cm^2, longitudinal dimensions of the burning zone of the order of $\Delta x \approx$ 50 cm, the degree of burnup of ^{238}U is 81%. It should be noted that the huge values of the specific power of 1.2 GW/cm^3 at the maximum of the burning wave and the high neutron fluency in the material of $5 \cdot 10^{24}$ n/cm^2 behind the burning wave are significant. Satisfactory agreement is observed between the results obtained by the modeling method and the analytical results of [8].

The values of the Feoktistov wave parameters are the maximum values that can be achieved in a Teller reactor in emergency operation, so the data obtained can be used to consider safety issues for this type of reactor.

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МОДЕЛЮВАННЯ КОДОМ MCNPX ХВИЛІ ГОРІННЯ ФЕОКТИСТОВА, ЩО БІЖИТЬ, В УРАНІ

В.В. Ганн, Г.В. Ганн

Проведено математичне моделювання хвилі ядерного горіння Феоктистова, що біжить, у збідненому урані методом Монте-Карло з використанням програми MCNPX, доповненої зворотним зв'язком по реактивності з метою знаходження значення стаціонарної потужності системи. Отримано значення швидкості V = 2,8 см/сут і наведеної потужності хвилі горіння, що біжить, р = 35 МВт/см^2.