

Evaluation of the neutronic performance of a fast traveling wave reactor in the Th-U fuel cycle^{*}

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Abstract

The possibility for all of the uranium or thorium fuel to be used nearly in full is expected in traveling wave reactors. A traveling wave reactor core with a fast neutron spectrum in a thorium-uranium cycle has been numerically simulated. The reactor core is shaped as a rectangular prism with a seed region arranged at one of its ends for the neutron fission wave formation. High-enriched uranium metal is used as the seed region fuel. Calculated power density dependences and concentrations of the nuclides involved with the transformation chain along the core at a number of time points have been obtained. The results were graphically processed for the clear demonstration of the neutron fission wave occurrence and transmission in the reactor. The obtained power density dependence represents a soliton (solitary wave) featuring a distinct time repeatability. Neutron spectra and fission densities are shown at the initial time point, when no wave has yet formed, and at the time of its formation. The wave rate has been calculated based on which the reactor life was estimated. The fuel burn-up has been estimated the ultra-high value of which makes the proposed reactor concept hard to implement. The burn-up of most of both the raw material and the fissile material it produces indicates a high potential efficiency of the developed reactor concept in terms of fuel utilization and nuclear nonproliferation.

Keywords

Traveling wave reactor, fuel utilization, thorium, nuclear combustion wave, nuclear concentration of nuclides, burn-up depth, reactor life

Introduction

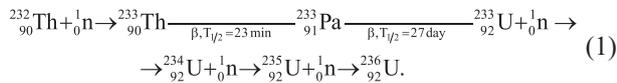
A great deal of attention is given in scenarios of nuclear power evolution to issues of fuel supply and fuel utilization at nuclear power plants. The specific nature of nuclear fuel combustion in the reactor core affects the plant's operating conditions, economics, and safety. The potential of nuclear power with only uranium-235 being in use is highly limited and fails to provide for the decisive advantages as compared with power technologies

based on other energy sources. Processed natural uranium enriched in the ²³⁵U isotope is used in traditional nuclear reactors, both fast and thermal. However, the fissionable isotope is combusted only in part, which reduces the efficiency and cost effectiveness of nuclear fuel utilization. Thus, the design burn-up of fuel in new-generation units with VVER reactors amounts to not more than 5.5% h.a. A higher burn-up (up to 7% h.a.) is reached in BN reactors, and the burn-up has been increased to 12% h.a. in the BN-600 reactor with a potential for bringing the

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maximum burn-up of fuel in the FAs to 15% h.a. An ultra-high burn-up (tens of percent) is potentially reachable only in high-temperature gas-cooled reactors (VTGR) being under development (Zverev 2018). However, most of the potential fuel (uranium-238) in natural uranium is not used in the existing reactors. A possible solution to the problem is to convert the raw material to fuel material in fast-neutron reactors with respective breeding characteristics within a closed fuel cycle. Thanks to breeding, such technology allows natural uranium to be used practically in full. The possibility for using nearly all of the uranium or thorium fuel is expected in traveling wave reactors (TWR). In the core of such a reactor, in the process of nuclear transformations, the raw material with the highest possible breeding performance converts to a fissile material (plutonium-239 or uranium-233), which, subsequently, undergoes fission while producing energy and further neutrons in the same fuel batch, that is without unloading and reprocessing, excluding so the potential for its diversion. The conceptual technological condition for an ultra-high burn-up to be achieved in such a reactor is survivability of fuel elements.

In the first approximation, a traveling wave reactor can be represented as a cylinder (or a parallelepiped) of a pure raw material, such as ^{238}U or ^{232}Th , irradiated by neutrons from its end. In the subsurface region of the cylinder defined by the length of the neutron path, the raw material (e.g., ^{232}Th) transmutes to a material fissionable in accordance with a chain of transformations:



As the critical concentration of the fissionable material is reached, a self-sustained chain reaction occurs and neutrons enter the adjoining region where the fissionable material starts to accumulate. Therefore, nuclear fission takes place throughout the raw material lengthwise the cylinder. The process of fissions is self-regulating since the fact of the fissile material concentration exceeding to any extent the critical concentration needs to be made up for by its burn-up during the time that is comparable with the neutron lifetime, and the new fissionable material forms for the time comparable with that of the precursor β -decay, and not simultaneously.

The possibility of the neutron fission wave formation in a fast reactor was first shown by S.M. Feynberg and Ye.P. Kunegin in (Feynberg and Kunegin 1958). Later, L.P. Feoktistov (Feoktistov 1989) proposed a theoretical description of and the conditions for the formation of a neutron fission wave. The nonlinear self-regulating TWR mode occurs thanks to a high coefficient of conversion from the breeding material to a fissionable material through the neutron absorption and the subsequent nuclei transformation. The key advantage offered by this reactor type is that, after the reactor enters the steady-state combustion wave mode without neutrons coming from the seed region, it does not require reactivity control and, so, the initial

fuel composition in the TWR will transmute in accordance with the neutronic processes with no outside interference or any refueling throughout the lifetime. In this mode, the reactor is automatically kept at a constant power in nearly a critical condition. In addition, a reactivity control system is required to compensate for the reactivity margin in the seed region, to compensate for the power reactivity effect, and to change the reactor power. The advantages inherent in such reactor type are high fuel utilization efficiency and no need for dedicated procedures to enrich the fuel for the feed region, as well as increased reactor safety. Tasks were solved based on the above concept using various approaches to and descriptions of the phenomenon in question, including nuclear combustion wave (Pavlovich et al. 2008), candle (Ismail et al. 2007), criticality wave (Van Dam 2000), traveling wave (Gilleland et al. 2016), etc. For example, (Van Dam 2000) deals with studying the stability of the nuclear combustion wave mode at the stage when the reactor already reaches the steady-state condition with constant values of the neutron flux in the system and the wave propagation velocity, as well as with studying the reactor behavior in conditions of particular external disturbances in neutron fields and of the fuel heterogeneity in the form of the fuel local initial enrichment in fissionable isotopes on the neutron fission wave propagation path. The analysis results have shown a remarkable stability of the traveling wave reactor with respect to the neutron flux disturbances and the possible fuel heterogeneity. This stability is the manifestation of a specific negative feedback inherent in the new mode. (Pavlovich et al. 2008) deals with studying the effects of the absorber concentration on the neutron fission wave propagation velocity and, as a consequence, on the reactor power. The authors have considered particular systems in which the neutron fission wave can propagate. A theory of disturbances, making it possible to calculate the fission wave velocity depending on the preset parameters, has been developed based on the obtained equilibrium conditions.

The characteristics of burn-up and the velocity of the combustion wave propagation in a small high-temperature gas-cooled reactor were studied in (Ismail et al. 2007). The use of thorium as fuel has become a feature of the considered reactor.

A new method for the neutron fission wave arrangement was proposed in (Chen et al. 2008). In a pebble-bed reactor, unlike the above-mentioned CANDLE concept, the neutron flux movement is substituted by the fuel movement. Evidently, these two types of movement are equivalent owing to the relative movement principle. The boundary value problem for the diffusion equation solving, linked to simplified burn-up equations, has been considered, and a more general solution has been obtained for a one-dimensional case which is referred to as the base burn-up mode. This solution has less limits on the fuel burn-up characteristics and expands the CANDLE burn-up concept to more general cases of the core with finite dimensions and, sequentially, nonzero boundary conditions.

Two fast reactor concepts are considered in (Kodochigov et al. 2014) based on one and the same principle:

according to one of the concepts, a fertile isotope is added to the fissionable isotope owing to the neutron flux movement or energy release along the initially formed composition consisting of the seed region and the blanket (the traveling fission wave concept), and, according to the other, the neutron flux movement is substituted by the movement of the fuel composition consisting of the fissionable material and the fertile material (the standing fission wave concept). The neutronic conditions for implementing the proposed fast reactor concept with an open uranium-plutonium cycle have been justified by calculation. The major problem involved in implementing the reactor with a wave energy release that provides for the natural uranium burn-up at a level of 50 to 60% and a prolonged life of 30 to 40 years is radiation stability of fuel.

A traveling wave reactor in a thorium-uranium fuel cycle was considered in (Pomysukhina et al. 2019) using the developed analytical model of the nuclear concentration change depending on the generalized fluence in the cylinder irradiated by neutrons from its end until the critical mass is achieved. The nuclear combustion wave formation and existence region was evaluated for reactors with thermal and fast neutron spectra. The key criterion accounting for the capability of the neutron fission wave arrangement is the fissionable material (uranium-233) concentration exceeding, at a certain time, its critical value in the layer adjacent to the neutron source. This indicates that the fission processes in the said fuel layer will exceed the accumulation processes, and the combustion region may serve the source of neutrons for the next adjacent fuel layer for similar nuclear processes to occur.

Methods and instruments

The traveling wave reactor core was numerically modeled in a thorium-uranium cycle as part of the study using the WIMS-D4 code. The reactor core is shaped as a rectangular prism of the length 970 cm. A 160 cm seed region with a lateral size of 186 cm is arranged at one of the prism's ends to form the neutron fission wave. Uranium metal with the 20% enrichment in ^{235}U is used as the seed region fuel. The fertile material region is 800 cm long and consists of a pure raw material, ^{232}Th . The seed region is the external source of neutrons which causes the raw material in the prism's subsurface layer to transmute to a fissionable material in accordance with nuclear transformation chains. The core is surrounded by the reflector along the edges (see Fig. 1). Uranium and thorium are used in the



Figure 1. Computational model of the traveling wave reactor: 1 – absorber region; 2 – seed region; 3 – reflector; 4 – fertile material region.

Table 1. Composition of the seed region and the fertile region.

	Volume fractions	Density, g/cm ³	Atomic weight	Concentration (barn·cm) ⁻¹
Seed region				
Uranium metal	0.438	18.7	U – 235 U – 238	0.004155 0.01662
Silicon carbide	0.162	3.2	Si – 28.09 C – 12	0.007785 0.007785
Helium	0.4	$6.64 \cdot 10^{-5}$	He – 4	$1 \cdot 10^{-5}$
Fertile region				
Thorium	0.438	11.5	Th – 232	0.01307
Silicon carbide	0.162	3.2	Si – 28.09 C – 12	0.007785 0.007785
Helium	0.4	$6.64 \cdot 10^{-5}$	He – 4	$1 \cdot 10^{-5}$

reactor in the form of pebbles of the diameter 35 mm with a silicon-carbide cladding.

The content and key performance of the fuel, the coolant, and the structural materials of the seed region and the fertile region are presented in Table 1.

The described reactor model burn-up was calculated using the WIMS-D4 code in a plane geometry calculation option. The seed region and fertile region compositions are homogenized. The whole of the reactor core is broken down lengthwise into 31 regions with a step of 32 cm. With the breakdown step reduced from 32 cm to 16 cm, the power density decreases by not more than 4% at its maximum, and changes by about 20% in the energy release (where small) wave tail region. The transport problem was solved at each burn-up step in a two-group energy approximation. The energy of 0.0091 MeV corresponding to the fission spectrum end serves the interface for the groups. It should be noted that the calculation in a 26-group approximation produces practically the same results.

A transport equation in an integral form was solved at the macroscopic cross-section preparation stage by collision probability method for the spectrum calculation in 69 energy groups. At the present time, the WIMS-D4 code uses the base nuclear constant library in 69 groups acquired based on UKNDL and ENDFB6 data.

To demonstrate in a clear-cut manner the existence and nature of the wave process in a fast reactor, the numerical simulation results were graphically processed. Fig. 2

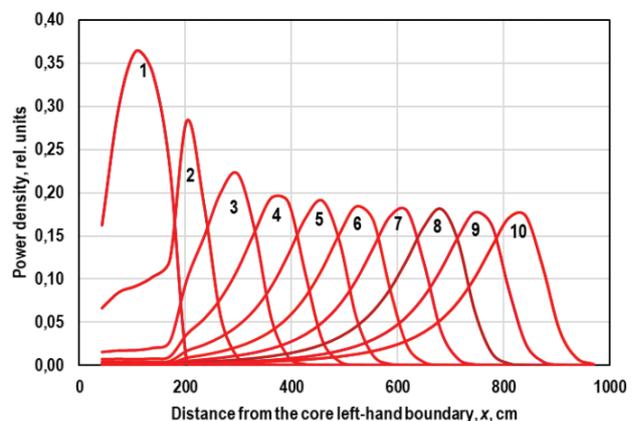


Figure 2. Power density distribution along the core after 100 days (1), 1000 days (2), 2000 days (3), 3000 days (4), 4000 days (5), 5000 days (6), 6000 days (7), 7000 days (8), 8000 days (9), and 9000 days (10).

shows the functional dependence of power density on distance for various reactor lifetime points. It is exactly in the power density diagram that the wave nature of the reactor dynamics can be observed the best. It can be seen from the figure that the obtained dependence represents a soliton (a solitary wave) featuring a distinct repeatability in time. In practice, however, we encountered the wave dispersion due to which the position of the power density maximums decreases with time.

Results and discussion

The neutron fission wave velocity has been found to be equal to 29 cm/year, and the considered reactor life is about 30 years. These results differ substantially from those obtained in (Petrov 2014) for a similar reactor operating in a uranium-plutonium cycle where the fission wave velocity was 11 cm/year. A higher combustion wave velocity in the considered reactor operating in a thorium-uranium fuel cycle is explained by a smaller concentration of thorium nuclei since the thorium density (11.5 g/cm^3) is much less than the density of uranium metal (18.7 g/cm^3). It is shown in (Pavlovich et al. 2008) that the wave velocity can be approximately estimated using the formula

$$u = P_t / (ESN_0\eta), \quad (2)$$

where P_t is the thermal power; E is the energy of one fission event; S is the wave cross-section area; N_0 is the concentration of heavy nuclei in the wave region; and η is the fraction of the fissioned nuclei during the wave transmission. In accordance with this formula, the wave velocity in the thorium region, all other parameters being equal, is expected to be nearly twice as high as in the uranium region, this being satisfactorily in line with our numerical estimates.

Fig. 3a shows the distribution of uranium-233 lengthwise the core for a number of the reactor lifetime points. It can be seen from the figure that the uranium-233 distribution has pronounced maximums which correspond to the combustion region. And the transverse uranium-233 concentration profile moves, over time, from the core's left-hand boundary to the opposite boundary. The neutron fission wave moves along the reactor in the same way.

Fig. 3b demonstrates the distribution of thorium-232 lengthwise the core at different reactor lifetime points. It can be seen from the figure that most of the raw material and the fuel it produces (uranium-235) burn up in a substantial portion of the core, this indicating a high potential efficiency of the considered reactor in terms of fuel utilization and nuclear nonproliferation. At the same time, an exclusively high burn-up of thorium (about 90%) makes such reactor hard to implement.

One of the essential tasks in studying the possibility for the wave process implementation is to render the reactor critical. The possibility for achieving the reactor criticality at the time the steady-state wave mode is entered in is shown in Fig. 4.

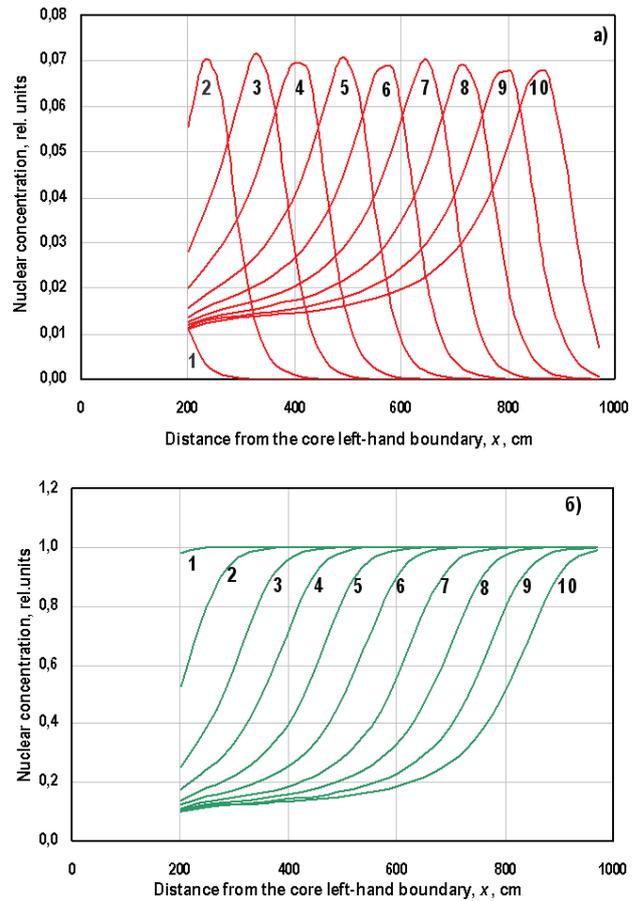


Figure 3. Change in the uranium-233 (a) and thorium-232 (b) nuclear concentration along the core after 100 days (1), 1000 days (2), 2000 days (3), 3000 days (4), 4000 days (5), 5000 days (6), 6000 days (7), 7000 days (8), 8000 days (9), and 9000 days (10).

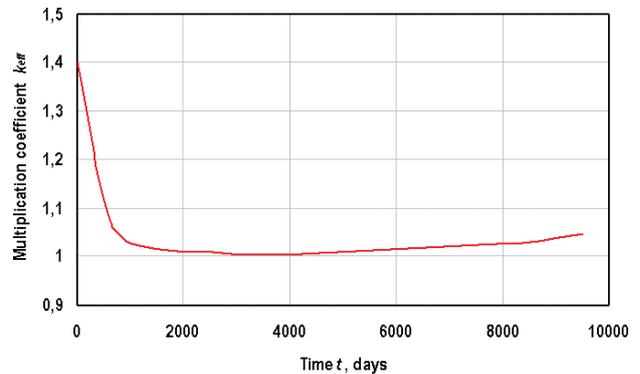


Figure 4. Effective multiplication coefficient behavior in time.

A feature of the modeled system behavior is that the effective multiplication coefficient drops at the initial time point as fuel burns up in the seed region while the energy release wave mode has not yet formed. At the time when k_{eff} stops to drop, the reactor enters the energy release wave mode and the multiplication coefficient profile stabilizes. Owing to the initial reactivity margin to the wave mode formation, the existing seed region makes the reactor safety level to decline. This requires the reactivity monitoring and control measures and facilities inherent in traditional plants, including in case of unlikely accidents.

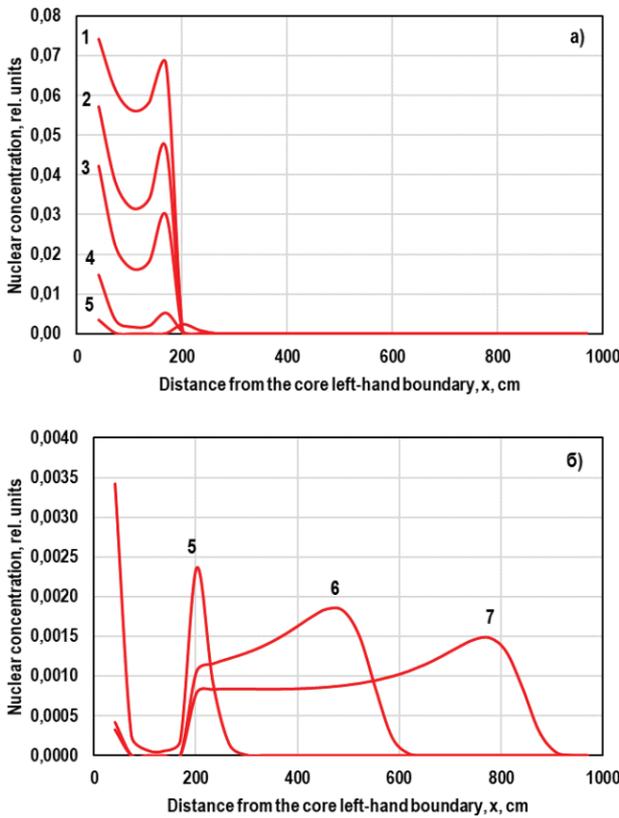


Figure 5. Change in the uranium-235 nuclear concentration lengthwise the core after 100 days (1), 200 days (2), 300 days (3), 500 days (4), 1000 days (5), 5000 days (6), and 9000 days (7): a) – seed region; b) – feed region.

The seed region burning time is observed in Fig. 5 with dependences of the uranium-235 concentration change lengthwise the core at some of the life times. It can be seen from the figure that the uranium-235 concentration lengthwise the core becomes practically zero after 1000 days. A certain amount of uranium-235 also forms in the feed region in connection with radiation captures of neutrons by uranium-234.

Figs 6, 7 show the neutron and fission density spectra for different fission wave positions: at the initial time point when no wave has yet formed, and after about 2000 days when the reactor operates in the fission-wave mode.

It follows from the comparison of the two final diagrams that the neutron spectrum and the fission density spectrum change substantially in the course of the fission wave transmission. The quantity of neutrons in the blanket grows though the spectra form does not change. Interestingly, the fission density in the seed region becomes constant for neutrons with all energies.

The values of the fuel burn-up in the core are calculated using the formula

$$q(x) = \frac{N^{Th2}(0) - (N^{Th2}(x) + N^{U3}(x) + N^{U4}(x) + N^{U5}(x) + N^{U6}(x))}{N^{Th2}(0)}, \quad (3)$$

where $N^{Th2}(0)$ is the initial concentration of thorium-232; and $N^{Th2}(x)$, $N^{U3}(x)$, $N^{U4}(x)$, $N^{U5}(x)$, $N^{U6}(x)$ are the concentrations of thorium-232, uranium-233, uranium-234,

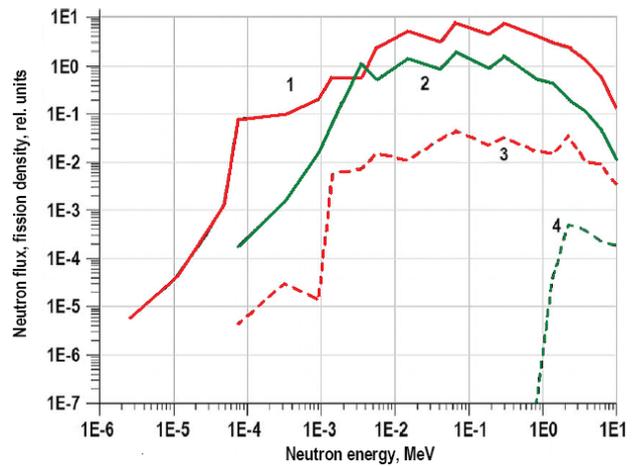


Figure 6. Neutron and fission density spectra at the fission wave formation start time: 1, 2 – flux spectra in the seed region area and in the adjacent breeding region (blanket) respectively; 3, 4 – fission density spectra in the seed region and in the blanket.

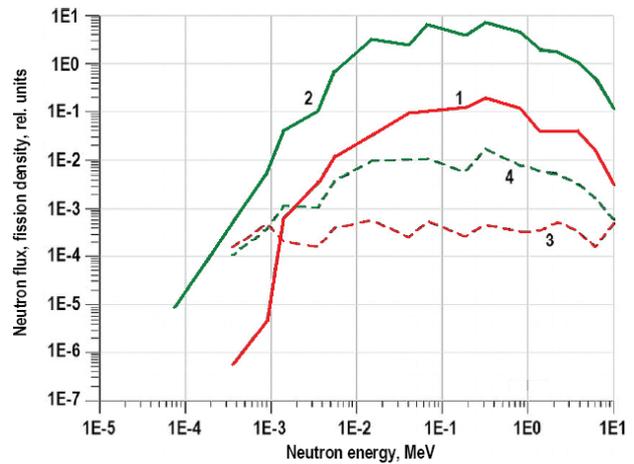


Figure 7. Neutron and fission density spectra after 2000 days from the reactor fission-wave operation start time: 1, 2 – flux spectra in the seed region area and in the blanket respectively; 3, 4 – fission density spectra in the seed region and in the blanket.

uranium-235, and uranium-236, respectively, in different core portions.

Fig. 8 shows the results from the calculation of burn-up as of the life end. It can be seen from the diagram that the burn-up reaches nearly 90% after 9000 days of operation.

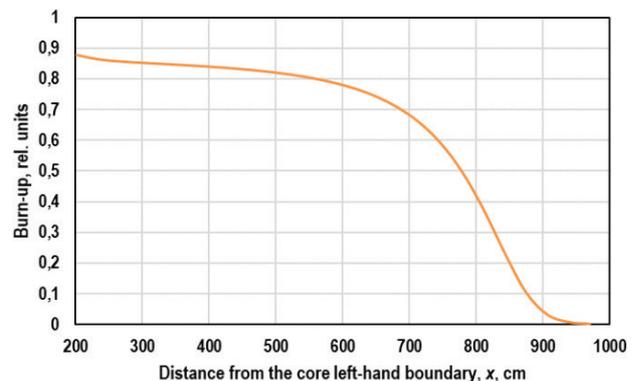


Figure 8. Fuel burn-up lengthwise the core after 9000 days.

Table 2. Key core parameters.

Parameter	Value
Seed region	
Lateral size, cm	186
Length, cm	160
Buckling, cm^{-2}	0.000193
Reflector thickness, cm	10
Fertile region	
Lateral size, cm	186
Length, cm	800
Buckling, cm^{-2}	0.000193
Reflector thickness, cm	10
Power density, MW/t	66.7

Conclusion

Simulation of the traveling wave reactor confirms the possibility for the wave process existence in a fast reactor with thorium fuel. The velocity of the neutron fission wave in a reactor with a seed region, containing ^{235}U -enriched fuel, has been calculated and found to be equal to 29 cm/year. At the same time, the approximate life of the considered reactor will be about 30 years. Most of both the raw material and the fuel it produces (uranium-233) burns up in a substantial core portion

which indicates a high potential efficiency of the considered reactor in terms of fuel utilization and nuclear nonproliferation. The burn-up reaches nearly 90% at the life end. The task to provide the engineering support for such an ultra-high burn-up and, accordingly, a prolonged life of 30 years and more should be solved through using coated-particle fuel with a silicon-carbide cladding in a fast reactor.

It should be noted, however, that the considered concept of the traveling wave reactor is not a closed one since a uranium-containing seed region with the 20% uranium-235 enrichment is required to start up each such thorium combustor reactor, for which purpose three extra facilities need to be in operation: those for uranium mining, uranium enrichment, and uranium fuel fabrication. It should be also noted that the use in the seed region of uranium metal having no high radiation stability may turn out improper. Its radiation stability can be increased through alloying additions. Besides, it is required to give a separate consideration to the problem of handling the unloaded fuel which has a high decay heat level and contains much uranium-235 being quite fit for the nuclear weapon manufacturing.

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