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NUCLEAR BURNING WAVE MODULAR FAST REACTOR CONCEPT

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Abstract - *The necessity to provide nuclear power industry, comparable in a scope with power industry based on a traditional fuel, inspired studies of an open-cycle fast reactor aimed at:*

- solution of the problem of fuel provision by implementing the highest breeding characteristics of new fissile materials of raw isotopes in a fast reactor and applying accumulated fissile isotopes in the same reactor, independently on a spent fuel reprocessing rate in the external fuel cycle;

- application of natural or depleted uranium for makeup fuel, which, with no spent fuel reprocessing, forms the most favorable non-proliferation conditions;

- application of inherent properties of the core and reactor for safety provision.

The present report, based on previously published papers, gives the theoretical backgrounds of the concept of the reactor with a nuclear burning wave, in which an enriched-fuel core (driver) is replaced by a blanket, and basic conditions for nuclear burning wave initiating and keeping are shown.

I. INTRODUCTION

It is hard to imagine that the energy demand of the evolving world community could be satisfied without a large-scale growth in the nuclear energy. However, specialists' and public's concerns about potential hazards of nuclear technologies provide an incentive for the continuous search for new ideas and solutions for most comprehensive use of the advantages of nuclear energy with indispensably enhancing nuclear and radiation safety, environmental acceptability and proliferation resistance. Many of currently proposed innovations were delineated at the dawn of the nuclear power industry. In that respect, at the 2nd International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958 (Discussions of paper No. 419 and 1848, 1958), S.M. Feinberg with reference to E.P. Kunegin's calculations expressed an idea of the breeder reactor wherein the breeding fuel travels in the core while supporting fission in irradiated fuel that does not need chemical reprocessing. In this suggestion, depleted or natural ^{238}U is loaded into the reactor, and the produced fissile plutonium isotopes sustain criticality. According to calculations, the reactor reaches the burnup of 30% h.a. before the built-up fission products render the reactor subcritical. Later on, in different countries of the world, studies have been carried out in this area [1-17]; however, the concept has not advanced beyond theoretical substantiations.

The demand for fuel in the nuclear power industry comparable in its scale to that in the power industry utilizing conventional fuel has provided an incentive for our research into the open cycle fast reactor concept that aims to:

– solve the problem of fuel supplies by implementing, in a fast reactor, the highest characteristics for breeding new fissile materials from fertile isotopes and by using, in the same reactor, the built-up fissile isotopes independently of the spent nuclear fuel (SNF) reprocessing rate in the external fuel cycle,

– use natural or depleted uranium for the makeup fuel, which creates the most favorable conditions for maintaining the non-proliferation mode considering the fact that there is no SNF reprocessing,

– use inherent properties of the core and reactor itself to ensure safety.

Based upon earlier published works, this paper provides theoretical prerequisites for reactor concept substantiation; the main conditions for initiation and maintaining of the nuclear burning wave are shown.

II. TRAVELLING WAVE REACTOR (TWR) CONCEPT

Recently, the S.M. Feinberg's idea has been implemented in a widely spread reactor concept utilizing the travelling neutron-fission wave. In its current shape, this idea was suggested for the first time by L.P. Feoktistov [1, 2]. The idea is based upon the possibility of developing a fast neutron reactor that can operate unmanned for a long time. In addition to the long-time reactor fuel cycle and the reactor self-control possibility, a substantial advantage of the TWR over current reactor plants is nuclear fuel burnup efficiency that could be higher by several times than the current values in conventional fast reactors. The Feoktistov's concept is based upon the use of an external neutron source.

The reactor core design can be visualized as a cylinder made of pure fertile material, like ^{238}U or ^{232}Th, that is irradiated by neutrons on its end (See Figure 1). In so doing, the feed material in the near-surface region that is defined by the neutron path length transmutes into fissile material according to the following transformation chains:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \xrightarrow[\beta, T_{1/2}=23.5min]{} ^{239}_{93}Np \xrightarrow[\beta, T_{1/2}=2.3day]{} ^{239}_{94}Pu$$

$$^{232}_{90}Th + ^{1}_{0}n \rightarrow ^{233}_{90}Th \xrightarrow[\beta, T_{1/2}=22min]{} ^{233}_{91}Pa \xrightarrow[\beta, T_{1/2}=27day]{} ^{233}_{92}U$$

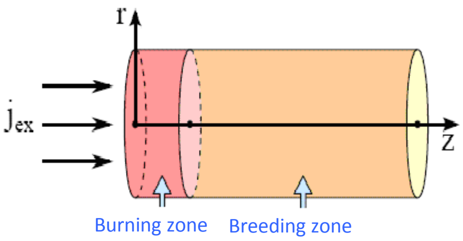

Fig. 1: Reactor model.

When the critical concentration of fissile material is reached, a self-sustaining chain reaction starts, and neutrons are supplied to the adjacent region wherein buildup of fissile material starts, and energy release is localized in this region etc. Thus, the slow nuclear fission wave propagates in the fertile material. Such wave is self-controlled because any fluctuation of fissile material concentration in excess of the critical one should burn over the time comparable with the neutron lifetime, and the new fissile material is generated over the time comparable with the β-decay time of the precursor and not simultaneously.

If plutonium is the new fissile material, the self-sustaining fission reaction in such reactor starts after the fissile ^{239}Pu concentration of a certain value is reached that is defined by correlation between the uranium and plutonium cross-sections in the hard spectrum:

$$N_{cr}=\sigma^{238}{}_{c}/(\nu-1)\sigma^{239}{}_{f}, \qquad \text{(eq. 1)}$$

which is 7–8%.

One important condition was identified by Feoktistov, namely, the critical concentration of the fissile material should be lower than its equilibrium concentration (with $t\rightarrow\infty$, defined as asymptotic solution to the kinetics equation for the fissile element concentration). One more necessary condition for existence of the fission wave is that K_∞ in the fission zone should be greater than unit, and in the previous and subsequent zones, it should be less than unit. Thus, in the ^{238}U medium under definite conditions, the neutron fission wave can propagate, and in the wave front, uranium captures neutrons and transforms into plutonium. This is a typical autowave mode that is being intensively studied in the non-linear physics.

The stationary mode of the slow nuclear burning wave has been studied by several groups. In references [8-10], numeric simulations are done for different options of fast reactors in the multi-group diffusion approximation with account of spatial and temperature effects. The authors gave a new name to the autowave mode—CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor)—which is quite illustrative because the TWR is evidently similar to a common candle.

The S.M. Feinberg's original idea is developed by Chen, Zhang and Maschek [17] in their paper where core physics with traveling fuel is studied—with axial travel and with radial reloading of fuel. Connection between this model and TWR is mentioned because of relativity between fuel and neutron flux travels.

Recently, studies on the idea of developing a nuclear fission wave reactor have been in progress in the USA in the breed-and-burn reactor design funded by Bill Gates, Terra Power, and also in the EM^2 design.

References [18,19] consider a possibility of implementing a nuclear burning wave in the flat and cylindrical core geometries in a fast reactor that consists of an axial seed zone with enriched fuel and an extensive zone of fertile material (natural uranium).

Theoretical prerequisites for substantiating the travelling fission wave concept are based upon analytical studies in references [12-17]. The simplest study of the problem presupposes that a diffusion single-group approximation should be considered, which is compliant with a non-linear diffusion equation with the isotopic composition changing in time. In the physical sense, it corresponds to balance ratio between neutron absorption, production and diffusion. In order to close the diffusion equation, it should be supplemented with burnup equations for isotopes. In fact, the level of details in the isotope burnup chain determines the precision of calculations; however, only a few of the isotopes—to be more exact, processes related to the isotopes—are key ones for TWR implementation.

To be definite, we will consider the uranium-plutonium cycle. It is more effective for fast reactors; and aside from that, the wave for the uranium-plutonium cycle has better characteristics from the viewpoint of the fuel utilization efficiency. For a start, let us write down equations that describe our system in a quite general form:

$$D(x)\Delta\Phi(x,t) + (\nu\sum_j \Sigma_f^j(x,t) - \sum_j \Sigma_a^j(x,t))\Phi = \frac{1}{V}\frac{\partial\Phi(x,t)}{\partial t}$$
(eq. 2)

where Φ is the neutron flux; ν is the number of secondary neutrons emitted by fission (we assume that it is the same for all fissile isotopes); $\Sigma_f^j = \sigma_f^j N^j$ is macro cross-section for the *j*-th nuclide; σ_f^j is the micro cross-section for the *j*-th nuclide (later on, we will assume that all micro cross-sections of elements are constant and do not depend on coordinates); N^j is the concentration of the *j*-th nuclide; $\Sigma_a^j = \sigma_a^j N^j$ is the macro cross-section of the *j*-th nuclide, where σ_a^j is absorption micro cross-sections of the *j*-th nuclide; V is the neutron velocity; *D* is the diffusion coefficient (generally speaking, it depends on the coordinate).

A more detailed transformation chain could be considered; however, because respective processes are insignificant and because expressions obtained in this case are bulky, there is sense in being limited to the following chain:

$$\frac{dN_8(x,t)}{dt} = -\sigma_a^8 N_8(x,t)\Phi(x,t)$$
$$\frac{dN_9(x,t)}{dt} = \sigma_a^8 N_8(x,t)\Phi(x,t) - \sigma_a^9 N_9(x,t)\Phi(x,t) - \lambda N_9(x,t)$$
$$\frac{dN_{Pu}(x,t)}{dt} = -\sigma_a^{Pu} N_{Pu}(x,t)\Phi(x,t) + \sigma_a^9 N_9(x,t)\Phi(x,t) + \lambda N_9(x,t)$$
$$\frac{dN_0(x,t)}{dt} = \sigma_c^{Pu} N_{Pu}(x,t)\Phi(x,t) - \sigma_a^0 N_0(x,t)\Phi(x,t)$$
$$\frac{dN_{fpp}(x,t)}{dt} = \sigma_f^{Pu} N_{Pu}(x,t)\Phi(x,t) + \sigma_f^0 N_0(x,t)\Phi(x,t) - \sigma_a^{fpp} N_{fpp}(x,t)\Phi(x,t)$$
(eq. 3)

Here N_i is concentrations of ^{238}U, effective nuclide, neptunium (N_9), ^{239}Pu, ^{240}Pu and fission products (*fpp*), respectively.

As the boundary conditions, the following will be used:

$$\begin{Bmatrix} N_{i\neq 8}(x,t=0)=0, \\ N_8(x,t=0)=N_8(0) \\ \Phi(x,t=0)=0 \\ \Phi(x,t=t_{end})=0 \end{Bmatrix}, \qquad \text{(eq. 3}a\text{)}$$

with the meaning that in the initial moment, the core is totally filled with ^{238}U, and with the zero boundary conditions for the flux that correspond to the *fuel* condition and *ashes* condition—of the burned up fuel—where t_{end} has the sense of the reactor fuel cycle.

The function in brackets in the expression (2) has the sense of the neutron generation function, which is a linear function of nuclide concentrations.

$$g(N) = \nu\sum_j \Sigma_f^j(x,t) - \sum_j \Sigma_a^j(x,t) \quad . \qquad \text{(eq. 4)}$$

It is evident that the neutron generation function characterized by the difference between the neutron production and absorption processes in the unit volume over a unit time is $\begin{matrix} g(x,t=0)<0, \\ g(x,t=t_{end})<0 \end{matrix}$, because the system is subcritical at the beginning (BOC) and the end (EOC) of cycle.

Let us find the solution for the equation (2) as a wave. For this purpose, let us introduce a dimensionless wave coordinate $z = \frac{x+ut}{L_0}$ and let us require that unknown functions depend only on *z* (exactly this will correspond to the solution as a wave). Here *u* is the wave speed, and L_0 is the diffusion length at BOC.

Later on, let us consider that the diffusion coefficient does not depend on the coordinate; in other words, it is a constant. It is roughly valid for fast systems. Then, the equation (2) is transformed as follows:

$$\frac{D}{L_0^2}\frac{d^2\Phi}{dz^2} + g(N)\Phi(z) = \frac{u}{VL_0^2}\frac{\partial\Phi(z)}{\partial z} \quad . \qquad \text{(eq. 5)}$$

The expression on the right side with the wave speed to neutron velocity ratio will be negligibly small because we are interested in low wave speeds when the wave propagation process can be considered quasi-stationary. That is, neutron velocities are by many orders of magnitude higher than the speed of the slow burning wave—$u_{wave}/V_{neutron} \approx 10^{-7}$ for fast neutrons. It means that diffusion processes will be a lot faster than kinetic processes (concentration variation processes).

It is the interest to the slow wave that is evidently dictated by the fact that at low wave travel speed we can obtain reactor fuel cycle durations by an order of magnitude longer than in conventional reactors.

Now, if we pass over to dimensionless variables: $N_i \to \frac{N_i}{N_8(0)}$, $\sigma \to \frac{\sigma_i^j}{\sigma_a^8}$, $\Phi \to \frac{L_0}{u}\sigma_a^8\Phi$, we will obtain: $\frac{D}{L_0^2} = \Sigma_a(0) = \sigma_a^8 N_8(0) = 1$, where $N_8(0)$ is the initial concentration of ^{238}U; $\Sigma_a(0)$ is the total absorption cross-section in the initial moment.

As a result, the equation (5) can be transformed into the following form:

$$\frac{d^2\Phi}{dz^2} + g(N)\Phi(z) = 0 \qquad \text{(eq. 6)}$$

For convenience of the subsequent analysis, let us introduce dimensionless generalized fluence as: $\psi(z) = \int_0^z \Phi(z)dz$; then we will multiply the equation (6) by *dz'* and integrate it, and as a result, we will obtain: $\psi''(z) + G(N(\psi)) = 0$, where $G(N(\psi)) = \int_0^\psi g(N(\psi))d\psi$ is the fluence generation function, and the strokes denote the second derivative of the wave variable.

Let us make a few permissible simplifications:

– In the transformation chain, let us neglect the effective nuclide and its decay; in other words, let us consider that ^{239}Pu appears immediately after the radiation capture of a neutron. This is justified by the fact that isotope burning and buildup processes are a lot faster, and exactly these processes define the dynamics of the system.

– In the equation for the fission product concentration, let us neglect the summand related to occurrence of fission products due to the ^{240}Pu fission reaction, because in the high-energy region ^{240}Pu fission cross-section is by far less than the ^{239}Pu fission cross-section.

While passing over to the wave variable and dimensionless form, we obtain the following:

$$\frac{dN_8(z)}{dz} = -N_8(z)\Phi(z)$$

$$\frac{dN_{Pu}(z)}{dz} = -\gamma \cdot N_{Pu}(z)\Phi(z) + N_8(z)\Phi(z)$$

$$\frac{dN_0(z)}{dz} = (\gamma - b)\cdot N_{Pu}(z)\Phi(z) - a\cdot N_0(z)\Phi(z)$$

$$\frac{dN_{fpp}(z)}{dz} = b\cdot N_{Pu}(z)\Phi(z) + a\cdot N_0(z)\Phi(z) - m\cdot N_{fpp}(z)\Phi(z)$$

(eq. 7)

where $\gamma = \frac{\sigma_a^{Pu}}{\sigma_a^8}$, $b = \frac{\sigma_f^{Pu}}{\sigma_a^8}$, $a = \frac{\sigma_a^0}{\sigma_a^8}$, $m = \frac{\sigma_a^{fpp}}{\sigma_a^8}$ are relative reaction cross-sections.

While again passing over to the generalized fluence $\psi(z) = \int_0^z \Phi(z)dz$, we can solve the system (7) with respect to $\psi(z)$. Thus, we will be able to describe isotope concentration behavior in terms of the generalized fluence, and this means that we will know the form of the fluence generation function, which will make it possible to express the neutron flux via the generalized fluence.

Eventually, the configurational space of the system is determined by variables (*N*, ψ) where the phase space is (*N*, $\psi, \psi' = \Phi$). While transferring from the initial state to the final state, the fluence ψ is steadily increasing from 0 to ψ_{end}. Therefore, we can consider that *N* and $\psi' = \Phi$ are functions of ψ on the phase trajectory.

To illustrate it, this reasoning can be represented as a scheme:

$$x,t \to z \to \psi(z), \quad N(x,t), \Phi(x,t) \to N(z), \Phi(z) \to N(\psi), \Phi(\psi).$$

After these transformations, solutions can be found for burnup equations. Let us write out the final solution right away:

$$N_8(\psi) = \exp(-\psi),$$

$$N_{Pu}(\psi) = \frac{1}{(\gamma-1)}[\exp(-\psi) - \exp(-\gamma\psi)],$$

$$N_0(\psi) = \frac{(\gamma-b)}{(\gamma-1)}[\frac{1}{a-1}\cdot(\exp(-\psi)-\exp(-a\psi)) + \frac{1}{a-\gamma}\cdot(\exp(-a\psi)-\exp(-\gamma\psi))],$$

$$N_{FPP}(\psi) = \frac{b}{(\gamma-1)}[\frac{1}{m-1}\cdot(\exp(-\psi)-\exp(-m\psi)) - \frac{1}{m-\gamma}\cdot(\exp(-\gamma\psi)-\exp(-m\psi))],$$

$$\Phi(\psi) = \sqrt{2(0.244\psi + 0.024\cdot\exp(-\gamma\psi) + 7.583\cdot\exp(-m\psi) - 6.343\cdot\exp(-\psi) - 1.264)}.$$

(eq. 8)

Values given in Table 1 for cross-sections averaged in the reactor spectrum with the average energy of around 0.2 MeV, provide a possibility of explicitly expressing the flux and nuclear concentrations as a function of generalized fluence.

Table 1: Values of averaged micro cross-sections.

Cross-section (barn)				
Elements	Absorption	Fission	Relative cross-sections	
U238	0.23	0	1	0
Pu239	1.92	1.68	8.348	7.304
Pu240	0.5	0.1	2.174	0.435
FPP-fission products	0.2	0	0.869	0

Knowing all concentrations, consequently we will find the function of neutron generation determined by the formula (4), as well as a multiplication coefficient in the endless medium that is determined as $K_{inf} = \frac{\nu \sum_j \Sigma_f^j(x,t)}{\sum_j \Sigma_a^j(x,t)}$, i.e. as a ratio of the number of generated neutrons to the number of absorbed neutrons.

Note that the multiplication coefficient in the endless medium completely determines the nature of kinetic processes. With K_{inf} <1, the system is subcritical; the state with K_{inf} =1 corresponds to the stationary critical case of a reactor with infinite dimensions (no neutron leakage); with K_{inf} >1, the reactor is supercritical.

Let us impart a specific form to the expression for the multiplication coefficient in the endless medium:

$$K_{inf} = \frac{\nu(b \cdot N_{Pu} + s \cdot N_0)}{N_8 + \gamma \cdot N_{Pu} + m \cdot N_{fpp} + a \cdot N_0}, \qquad \text{(eq. 9)}$$

where $s = \frac{\sigma_f^0}{\sigma_a^8}$ is the relative cross-section of the ^{240}Pu isotope.

For a fast reactor core, the second summand in the numerator (9) is by far less than the first summand. This is because the ^{239}Pu fission cross-section is by far greater than the ^{240}Pu fission cross-section for energies above ~0.2 MeV. Considering the last observation, the expression for the critical concentration of plutonium will be as follows:

$$N_{Pu}^{crit} = \frac{N_8 + m \cdot N_{fpp} + a \cdot N_0}{(\nu \cdot b - \gamma)}. \qquad \text{(eq. 10)}$$

The obtained expressions (8), (9) and (10) enable formulation of the conditions for existence of the nuclear burning wave:

1) The first condition for the reactor to meet, such that a wave could exist in it, was proposed by Feoktistov. The point is that the equilibrium concentration of fissile material (in our case, it is plutonium) should be higher than the critical concentration. Then, critical conditions could be achieved in the course of plutonium buildup.

$\tilde{N} = \frac{\sigma_a^8}{\sigma_a^{Pu}}$ is the equilibrium concentration (because $\sigma_a^8 = \sigma_c^8$, i.e. uranium does not take part in the fission process), *the condition superimposed onto the wave:* $N_{Pu}^{crit} < \tilde{N}$.

2) The process of intensive burning of the nuclear fuel—the wave region—starts from the moment the plutonium concentration exceeds the critical concentration.

However, a stronger condition is required for the system to meet if there is a neutron fission wave propagating in the system. This condition is a consequence of the transport equation (6) being analogous with the stationary Schrodinger equation. The analogy could be better illustrated if the transport equation (6) is written in the following form:

$\frac{d^2\Phi}{dz^2} = \Phi \cdot (1 - \frac{N_{Pu}}{N_{crit}})$, then the role of the potential in the Schrodinger equation is performed here by the inverted profile of plutonium concentration.

This allows writing down the critical condition for wave existence as follows:

$$I = \int \sqrt{(\frac{N_{Pu}(z)}{N_{crit}(z)} - 1)}dz = \pi/2, \qquad \text{(eq. 11)}$$

where the integral is taken over the supercritical region ($N_{Pu} > N_{crit}$). In our problem, it is the area of the region between two curves in Figure 2 from the fluence equal to 0.2 to the fluence equal to 0.7.

The condition (11) is nothing but the Bohr-Sommerfeld quantization condition transformed for our system.

In our example, condition (11) is satisfied with the accuracy of up to 7%. More precise coincidence is not required at least because the quantization condition itself for the lower level is approximated.

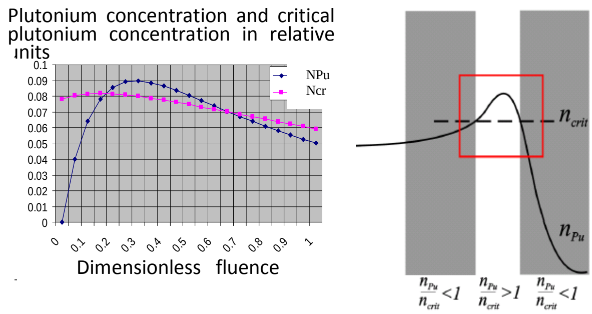

Fig. 2: Plutonium concentration behavior as a function of fluence.

In order for the wave mode to exist, it is required that the area of the supercritical region had a quite definite value. This requirement comes from the Bohr-Sommerfeld quantization condition. Otherwise, the wave may "stop".

Figure 2, on the right, shows a graph illustrating the analytical dependence of plutonium concentration behavior. It is shown that a region exists—the so-called "burning region"—where the plutonium concentration exceeds the critical concentration. Precisely in this region, the main burning of fuel takes place. The Figure illustrates two dependences. On the one hand, it shows plutonium concentration as a function of time for one of the cells that we use to break down the core (the time here goes from right to left). On the other hand, it is also concentration distribution over the coordinate in an arbitrary moment of time (from left to right).

Figure 3 shows nuclear concentrations and multiplication coefficient in the breeding zone as a function of dimensionless fluence.

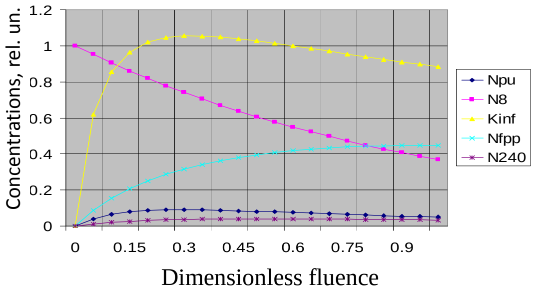

Fig. 3: Nuclear concentrations and multiplication coefficient as a function of fluence.

In this case, the intensive burning region is in the fluence interval $\psi/\psi_m \in [0.2;0.7]$. It is evident that with time in the operating reactor, the initial fuel load, that is ^{238}U, will be burning up according to the exponential law, whereas the concentration of generated fission products at a certain moment reaches its maximum that characterizes the intensive nuclear burning region, whereupon the fission product concentration starts to gradually reduce, which corresponds to the travel of the wave front to the adjacent region. At the same time, the fission product concentration is constantly growing throughout the process. Note that despite the hard neutron spectrum (small fast neutron capture cross-sections compared with the capture cross-sections for the thermal spectrum), the role of neutrons remains a key role for the physics of the process. The buildup of fission products that absorb neutrons is a stabilizing factor for the wave mode to form.

Behavior of the multiplication coefficient for a small region around an arbitrary point in the core is more illustrative for the wave process physics. This behavior determines the character of nuclear fuel burning in the core. One can see from the graph that initially the multiplication coefficient is growing because the fertile fuel is transforming into fissile material and the fissile material is building up. When the multiplication coefficient becomes greater than one, which corresponds to the intensive burning mode, the plutonium concentration starts to reduce alongside with the constant growth in fission product concentration. With time, this results in that the multiplication coefficient reduces and goes down to the subcritical values. Thus, the travel of the wave across the core is fully illustrated by the said graph. The reduction in the multiplication coefficient denotes departure of the wave from the said region and its gradual travel to the adjacent region.

Figure 4 illustrates relation between the flux and dimensionless fluence.

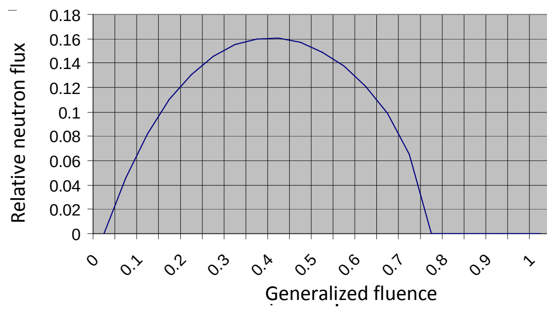

Fig. 4: Relation between the neutron flux and dimensionless fluence.

Physically, the wave propagation process can be explained as follows. The propagation of the neutron fission wave in fact is a propagation process for two waves going in the same direction. Both the waves move at the same speed determined by the composition of the medium, initial external neutron source (or, which is the same, by enrichment of the seed zone) and assigned thermal power. This speed is the neutron fission wave propagation speed. In the front position, the buildup wave moves that transforms the fertile material into the fissile material. Behind it, the burning wave follows that burns the generated fuel. Note that the burning wave goes with a little delay. This delay is explained by a delay in arrival of plutonium that is generated only in around three days after the neutron capture by the uranium nucleus. As a result, there is a certain time difference between the waves, which—together with the wave propagation speed—determines spatial distance between the buildup and burning waves.

Now, if the neutron fission wave speed is sufficiently high, the difference in the distance between the buildup wave and burning wave may exceed the diffusion length, in which case the wave will stop.

If the wave speed is comparatively low, the wave propagation will be impossible because the buildup wave and the burning wave will be in the same point and no successive transport will be there.

This also speaks about the fact that for the wave to exist a quite definite ratio of nuclear concentrations in the breeding zone is important. Figure 5 explicitly illustrates this provision.

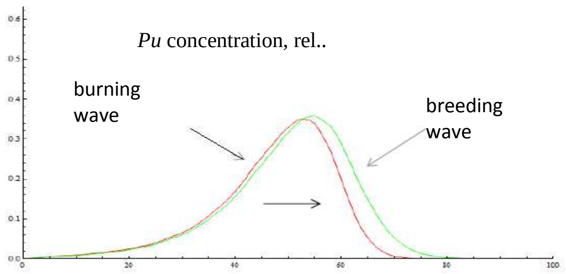

Fig. 5: For explanation of the wave propagation mechanism.

Illustrative is the following expression for the wave speed that is determined via the thermal power of the reactor [17]:

$$u = \frac{P}{\Delta E \cdot S \cdot N_0 \cdot \eta}, \qquad \text{(eq. 12)}$$

where P is the thermal power, MW; u is the neutron fission wave speed, cm/year; S is the wave transversal cross-section area cm^2; N_0 is the initial concentration of heavy nuclei, (barn cm)$^{-1}$; η is the fraction of nuclei fissioned by the passing wave; ΔE is the energy released by a single fission event, MeV.

One can see from the expression (12) that with the increase in the transversal size of the reactor (diameter), we reduce the wave speed. Evidently, this relates to the increase in the total mass of heavy nuclei—the more of them available, the longer the burning goes. It also follows from here that in order to obtain the lower wave speed, namely it is reasonable for providing a longer reactor fuel cycle, it is necessary to use high-density fuel—metallic uranium, of which density is almost twice higher than that of the conventional oxide fuel. Reference [20] shows that metallic uranium fuel is the only option in which conditions are met for initiation of the nuclear burning wave.

III. IMPLEMENTATION OF THE TRAVELLING NUCLEAR BURNING WAVE REACTOR CONCEPT

The described reactor concept may be implemented in reactors of two types: (1) reactor with a seed zone with enriched uranium fuel, which replaces the external neutron source, and fixed breeding zone wherein the wave propagates; (2) reactor with moving seed and breeding zones wherein fuel moves, and power distribution does not practically change its axial position in the core. The second reactor concept is the most easy to implement in the pebble bed core containing spherical fuel elements.

Results of numerical simulation related to the neutronic substantiation of the travelling or stationary nuclear burning wave reactor concept are given in reference [21].

IV. CONCLUSION

Based upon the latest publications dedicated to the traveling nuclear burning wave reactor, the paper provides theoretical prerequisites for the travelling process of the wave front in the breeding zone of the fast reactor.

Presented are conditions necessary for existence of the wave travel of power distribution.

Evaluated is the behavior of the main core characteristics, namely, nuclear concentrations of isotopes, multiplication coefficient.

Computational simulation results for substantiation of the described concept are provided in the paper [21].

REFERENCES

[1] L.P. Feoktistov, Neutron Fission Wave, USSR Academy Of Science Paper, vol. 309, pp. 864–867, 1989.

[2] L.P. Feoktistov, Safety as a Key Point for Nuclear Renaissance, Achievements in Physics Science, No. 8, pp. 89–102, 1993.

[3] E. Teller, Nuclear Energy for the Third Millennium, Preprint, UCRL-JC-129547, LLNL, 1997.

[4] H. Van Dam, Self-Stabilizing Critically Wave, Annals of Nuclear Energy, vol. 27, pp. 1505–1521, 2000.

[5] H. Van Dam, Flux Distributions in Stable Criticality Waves, Annals of Nuclear Energy, vol. 30, pp. 1495–1504, 2003.

[6] W. Seifritz, Solitary Burn-Up Waves in a Multiplying Medium, Kerntechnik, 65, pp. 5–6, 2000.

[7] X.-N. Chen, W. Maschek, Transverse Buckling Effects on Solitary Burn-Up Waves, Annals of Nuclear Energy, vol. 32, No. 12, pp. 1377–1390, 2005.

[8] H. Sekimoto et al., A New Burnup Strategy CANDLE, Nucl. Sci. Eng., vol. 139, pp. 306–317, 2001.

[9] H. Sekimoto, K. Tanaka, Application of CANDLE Burnup Strategy to Small Reactors, Trans. Am. Nucl. Soc., vol. 87, pp. 399–400, 2002.

[10] H. Sekimoto, Y. Ohoka, Application of Candle Burnup to Block-Fuel High Temperature Gas Reactor, Proc. of ICAAP'03, Cordoba, May 4–7, CD, Paper 3013, 2003.

[11] S.P. Fomin, Yu.P. Mel'nik, V.V. Pilipenko, N. F. Shul'ga, Investigation of Self-Organization of the Non-Linear Nuclear Burning Regime in Fast Neutron Reactors, Annals of Nuclear Energy, vol. 32, pp. 1435–1456, 2005.

[12] S.P. Fomin, Yu.P. Mel'nik, V.V. Pilipenko, N.F. Shul'ga, Study of Self-Organizing Regime of Nuclear Burning Wave in Fast Reactor, Problems of Atomic Science and Technology, No. 6, Series: Nuclear Physics Invest. (45), pp. 106–113, 2005.

[13] V.D. Rusov, V.N. Pavlovich, V.N. Vaschenko et al., Geoantineutrino Spectrum and Slow Nuclear Burning on the Boundary of the Liquid and Solid Phases of the Earth's Core, Journal of Geophysical Research, vol. 112, B09203, doi: 10.1029/2005JB004212, 2007.

[14] V.N. Pavlovich, Ye.N. Khotyaintseva, V.D. Rusov et al., Slow Nuclear Burning Wave Reactor, Atomnaya Energiya, vol. 102, No. 3, pp. 151–158, 2007.

[15] V.N. Pavlovich, V.N. Khotintsev, Ye.N. Khotyaintseva, Physics Basics of the Nuclear Burning Wave Reactor, Yaderna Physica ta Energetika, No. 2(24), pp. 39–48, 2008.

[16] V.N. Pavlovich et al., Physics Basics of the Nuclear Burning Wave Reactor. Specific Models, Yaderna Physica ta Energetika magazine, No. 39 (25), Ukraine, 2008.

[17] X.-N. Chen, D. Zhang and W. Maschek, Fundamental Burn-Up Modes of Radial Fuel Shuffling, International conference on mathematical and computation methods applied to nuclear science and engineering, 2011.

[18] K.G. Petrov, Yu. P. Sukharev, V.A. Chirkov, Traveling Neutron Fission Wave Reactor, Collected Proceedings of the 11th International Youth Scientific and Technical Conference *Future of Engineering Science*, NNSTU, Nizhny Novgorod, Russia, p. 263, May 18, 2012.

[19] K.G. Petrov, Explanatory Note for Master's Thesis, NNSTU n.a. R.E. Alekseev, 2013.

[20] I.A. Belov et al., Concept of Fast Reactors with the Open Fuel Cycle, Atomnaya Energiya, vol. 113, issue 2, pp. 67–73, August 2012.

[21] N.G. Kodochigov, Yu.P. Sukharev, Neutronic Aspects of Nuclear Burning Wave Modular Fast Reactor Concept Substantiation. Paper HTR2014-71099, 2014.