Approaches to slowing down the kinetics of a fast reactor as a means of enhancing its self-protection properties

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Abstract
The concept of slowing down the kinetics of a fast reactor, according to which a rapid reactivity insertion is used to reduce the development rate of transients at initial events, is aimed at achieving a higher level of reactor self-protection. The paper presents a set of studies on the engineering and technical implementation of this concept on the example of a high-power fast lead-cooled reactor. Considering a hypothetical initial event with a rapid insertion of a complete reactivity margin, the stability of the reactor with the slowed down kinetics in relation to such an event was analyzed. An updated physical-mathematical apparatus is proposed for evaluating the slowed-down kinetics and calculating the dynamics of transient processes. The basic principles for the formation of a reflector for such a reactor based on formulated criteria for slowing down the kinetics include the use of ^{208}Pb and weakly neutron-absorbing materials, as well as the optimum location of various structural elements in the reflector. The theoretical possibility of achieving a slowed-down kinetics in layouts that meet the developed principles is demonstrated.

Introduction

A new class of reactors combines the use of passive protection systems with the physical features of fast lead-cooled reactors to provide a sufficient level of self-protection for overcoming a failure of active reactivity control systems to prevent accidents [1–5].

Nuclear safety is currently based on inherent self-protection properties combined with the use of designed passive protection systems and measures that objectively limit the dangerous development of an emergency situation. Further development of nuclear safety consists in improving self-protection properties to a level where active protections and design constraints exceed those required for satisfactorily processing of transients, even in the case of the most conservative initial events. Such initial events include the most rapid possible insertion of the full reactivity margin at a rate unlimited by design solutions and other engineering considerations, i.e., almost instantaneous. Since the full reactivity margin at the minimum power level can significantly exceed the effective fraction of delayed neutrons, the implementation of such a hypothetical event entails a sharp power runout combined with a high rate of fuel heating. The most important aspect of reactor self-protection, which is similar to the approach implemented in a classical nuclear reactor using delayed neutrons, consists in the ability to smooth out abrupt processes by slowing down the neutron kinetics.

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Neutron-physical features of slowing down the kinetics of a fast lead-cooled reactor

The slowing down of kinetics in reactors is typically carried out naturally by means of delayed neutrons generated by the decay of fission products. However, this level of slowing down may be insufficient for the intended purpose. Following the same principle, the physical properties of the reactor should be such that, in addition to delayed ones, neutrons are generated that similarly affect the kinetics without impairing the neutronic properties of the fast reactor core.

The physical concept of a significant increase in the lifetime of only that proportion of fission neutrons that leak from the core of a fast reactor, and, following a long migration into the reflector, return to the core to cause a chain fission reaction with high probability, is discussed in [6, 7]. Since, under certain conditions, the migration time in the reflector may be 10^3–10^4 times longer than the lifetime of prompt neutrons in the core, a multiple increase in the average neutron lifetime may occur along with a natural slowing down of emergency processes. This concept is implemented by using a large weakly-absorbing neutron reflector.

When analyzing the neutron kinetics of this system, the fraction and average lifetime l^* of migrating neutrons that enter the reflector and then return to the core to cause the β^* division are important parameters.

The average lifetime of neutrons in the reactor l, excluding delayed neutrons, is determined by the weighted sum of prompt neutrons with a lifetime of l_{pr} and a time of l^*, so that

$$l = l_{\text{pr}}\left(1 - \beta^*\right) + l^*\beta^* \sim l^*\beta^*,$$

and the last transition can be performed due to the smallness of l_{pr} compared to l^*. The fraction of migrating neutrons β^*, estimated at ~0.1, is ten times higher than that of delayed neutrons, which is weakly dependent on the reactor layout and allows the insertion of a significant reactivity without the use of prompt core neutrons to carry out the acceleration. For comparison, the fraction of delayed neutrons in a lead-cooled reactor with an electric power of 1000 MW is ten times less than β^*. However, the average lifetime of migrating neutrons significantly depends on the layout of the reactor, primarily the reflector: it is this parameter that determines the change in the dynamics.

The different physical nature of migrating neutrons as compared to delayed ones determines the specifics of their influence on the neutron-physical characteristics of the reactor. In particular, delayed neutrons are generated almost evenly over the core volume (proportional to the power distribution), while the neutrons, which are slowed down as a result of the prolonged migration, enter the core from the reflector to cause fission in the peripheral fuel layer. Since the spectrum of migrating neutrons returning to the core differs from that of prompt and delayed neutrons, they form a slightly different distribution over the main reactions occurring in the core. However, in a simplified point model of the reactor kinetics, migrating neutrons can be described as an additional group of delayed neutrons. The modified equations of the point kinetics for an approximate two-zone reactor model comprising a core and a reflector, which are obtained by integrating an equation of a non-stationary neutron transfer throughout the reactor, will in this case be represented by a system having the form

$$\frac{dn(t)}{dt} = \frac{\rho - (\beta_{\text{eff}} + \beta^*)}{l_0} n(t) + \sum\nolimits_{i=1}^{6} \lambda_i C_i + \frac{C^*}{l^*}; \tag{1}$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{l_0} n(t) - \lambda_i C_i, \mathrm{i} = 1, \ldots, 6; \tag{2}$$

$$\frac{dC^*}{dt} = \frac{\beta^*}{l_0} n(t) - \frac{C^*}{l^*}, \tag{3}$$

where n—relative power of the reactor; ρ—reactivity; β^*—total effective fraction of migrating neutrons; l_0—average lifetime of neutrons in the core; l^*—average lifetime of migrating neutrons; λ_i, C_i, β_i—decay constant, number of source nuclei, and fraction of the i-th delayed neutron group ($i = 1$–6), respectively; β_{eff}—total effective fraction of delayed neutrons; C^*—number of migrating neutrons.

Effect of slowing down the kinetics on transients with a rapid reactivity insertion

In order to analyze the neutron-physical characteristics of a reactor with slowed-down kinetics, a computational model that reflects the design of a fast lead-cooled reactor with an electrical and thermal capacity of ~1000 and 2800 MW, respectively, is used. According to calculations carried out using the precision models of the MCNP-4C program, the average lifetime of all neutrons in a fast lead-cooled reactor with a large natural lead reflector is less than 1 µs, while the lifetime of prompt neutrons in the core is less than 0.5 µs.

The initial event with the rapid insertion of the full reactivity margin is most dangerous at a minimally controlled power level, when the reactivity margin—equal to about 0.0075 ($2.15\beta_{\text{eff}}$)—for the considered fast lead-cooled reactor is significantly higher than the effective fraction of delayed neutrons.

Transient calculations that implement the point approximation represented in expressions (1)–(3) were carried out according to the DINAR program [8]. In the simulation of transients, feedback processes due to the Doppler effect and thermal expansion of the fuel and the coolant are taken into account. In terms of the considered processes, the Doppler effect has the greatest influence. The calculations lead to the conclusion that slowing down the kinetics significantly reduces the power spike in the transients with a rapid insertion of the full reactivity margin (Fig. 1a). However, the same calculations show that the maximum temperature of the fuel, coolant, and fuel cladding depends little on the level of slowing down the kinetics, being mainly determined

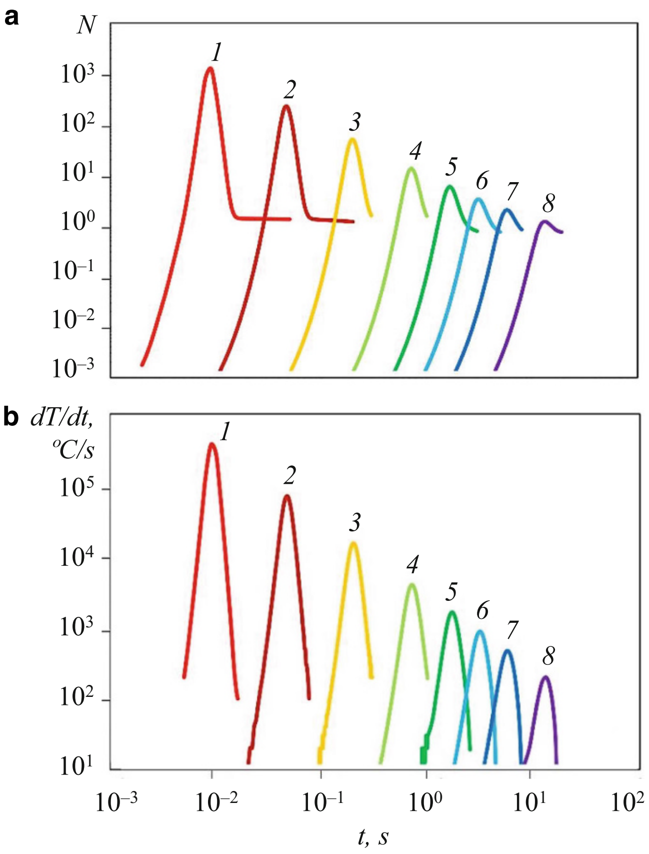


Fig. 1 Temporal dependence of the relative reactor power in rated power units (**a**) and maximum fuel temperature (**b**) at the rapid insertion of the full reactivity margin for the mean neutron lifetime of 1 (*1*), 10 (*2*), 50 (*3*), 200 (*4*), 500 (*5*), 1000 (*6*), 2000 (*7*), and 5000 (*8*) µs

Table 1 Dependence of critical parameters on the average lifetime of neutrons in a high-power lead-cooled reactor with the rapid insertion of the full reactivity margin

Average neutron lifetime, μs	Maximum power, nominal power units	Maximum fuel temperature growth rate, °C/s
1	1272	378,000
5	427	129,000
10	230	71,000
50	50	15,300
100	26	7790
200	13.4	3980
500	5.8	1650
750	4.2	1140
1000	3.4	880
1250	2.8	717
1500	2.5	609
2000	2	470
3000	1.5	325
4000	1.3	236
5000	1.2	199
10,000	0.9	105

by feedback processes. Thus, the most significant and sensitive parameter determining safety at the considered initial event is the growth rate of the fuel temperature, which, if unchecked, can lead to dangerous effects [4]. First of all, these include the impact destruction of the fuel core, the deformation and rupture of the fuel rod cladding, and the impact load on the lower support plate of the reactor core. Table 1 demonstrates that the rate of the fuel heating by slowing down the kinetics of the reactor can be reduced by several orders of magnitude. The heating of the fuel in systems having various average neutron lifetimes, which range from one to several thousand microseconds, is shown in Fig. 1b. Along with the maximum fuel temperatures depicted in Fig. 1a, this confirms the significance of the effect of slowing down the kinetics during the rapid emergency insertion of the full reactivity margin.

Required level of slowing down the kinetics

In the case of fast reactivity insertion, the most critical parameter is the fuel heating rate. Unfortunately, full information on the permissible limits of the heating rate is not currently available. In order to determine such limits, a set of experimental studies is required. However, the available data [9] indicate that a heating rate within 2000 deg/s does not lead to the shock destruction of the fuel matrix and the fuel rod.

According to the calculation analysis of the emergency dynamics carried out using the DINAR software complex to implement the system of equations (1)–(3), the maximum rate of the fuel heating in the transient due to the insertion of 0.0075 reactivity for the shortest time, which tends to zero, does not exceed 2000 deg/s at an average neutron lifetime in the reactor of 500 μs. This corresponds to the average lifetime of migrating neutrons equal to about 5000 μs at their fraction of 0.1. The level of slowing down the kinetics with the average neutron lifetime in the reactor of 500 μs can be considered as the minimum criterion limit.

Another approach to determining the required level of slowing down the kinetics is based on the principle of "equal hazards" [1]. Accordingly, when switching from a reactor whose safety is achieved using design restrictions to one where safety is ensured solely by means of internal self-protection, the consequences of emergency events should not deteriorate. This means that the rate of the fuel heating in a reactor with slowed-down kinetics at the rapid insertion of a full reactivity margin without limiting its rate should be less than in a reactor in which the kinetics at the insertion of a reactivity margin at a rate that is limited without slowing down by design solutions in accordance with the existing norms of 0.07 β_{eff}/s. According to calculations using the DINAR program, the fuel heating rate does not exceed 300 deg/s at such a limited velocity of the CPS CM movement in a fast lead-cooled reactor without slowing down the kinetics. In accordance with the calculated dynamics of the reactor with the slowed-down kinetics, the average life time of neutrons should be ~4000 μs for this heating rate (see Table 1).

Application of ^{208}Pb for slowing down the kinetics of a fast reactor

It should be noted that, due to the relatively moderate, but significant neutron absorption under these conditions, a reflector constructed using lead of a natural isotopic composition cannot be used to achieve the required average lifetime of neutrons, even at the large volumes of the reflector. At the same time, ^{208}Pb has unique properties as compared to conventional lead: about 10 times lower neutron absorption cross-section in the energy region characteristic of the fast reactor spectrum and several orders of magnitude lower cross-sectional absorption when the spectrum is softened. This is important under conditions of a large reflector volume, where migrating neutrons gradually lose their energy to the energy of epithermal neutrons. ^{208}Pb can be obtained by the isotopic separation of conventional lead or extracted from thorium ores, where its fraction reaches 95% [7].

Calculations carried out in the core model of a fast lead-cooled reactor without any structures show that the average lifetime of neutrons is ~2700 μs at a ^{208}Pb reflector having a thickness of 5 m. This means that the theoretical potential of slowing down the kinetics using ^{208}Pb is quite high.

However, merely replacing natural lead with ^{208}Pb while maintaining traditional steel structural elements in the reflector causes no significant effect in terms of slowing down the kinetics: the average lifetime of neutrons remains ~1 μs. This may be explained in terms of the important role played at such a replacement by the steel of structural elements located in the reflector, whose significant absorption of intermediate neutrons reveals no advantages of ^{208}Pb isotope.

A solution to this problem may be achieved by using structural reflector elements made of weakly neutron-absorbing materials. Such materials represent a popular and important component of a reactor in which slowed-down kinetics are at an increased level. From the neutron-physical point of view, graphite materials or ^{11}B$_4$C carbide are suitable for this purpose. When using them, the average lifetime of neutrons remains approximately at the level, which is typical for the lifetime of neutrons in a reactor with a ^{208}Pb reflector.

Layout for effectively slowing down the transient kinetics

Figure 2 shows the conventional lead-cooled reactor layout. The core is surrounded by areas with a large fraction of steel (fuel rods end caps and fuel assembly (FA) tops, side reflector units, CPS column, shell, support structures, etc.).

Under such conditions, it is extremely difficult to achieve a long lifetime of neutrons in the reflector. Since it is impossible to get rid of all neutron-absorbing structures, for example, reactivity controls should be located near the core; here, in order to achieve the required properties, it is necessary to use promising structural materials having a neutron capture cross-section comparable to that of ^{208}Pb for ensuring a weak neutron absorption in its individual parts of the reflector. It is advisable to locate steel structural components under the core, as well as on the side and top of the core, to form effectively slowing down areas of weakly neutron-absorbing structures.

Since the core geometrically represents a relatively small in height and large in a transverse diameter structure with a dominant end neutron leakage, the composition of the end reflector becomes of a particular importance. Therefore, it is recommended to use FAs in which the fuel is shifted upwards. In such FAs, a layer of structural

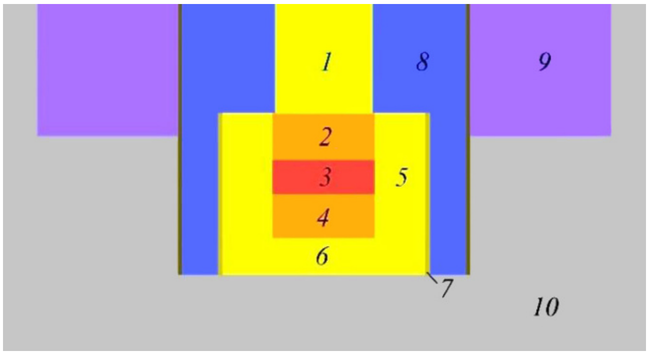


Fig. 2 Conventional layout of the lead-cooled reactor: *1*—CPS column; *2*—fuel rod and FA end caps; *3*—fuel; *4*—fuel rod and FA structures; *5*—side reflector; *6*—support structures; *7*—shell; *8*—lead; *9*—pump chambers; *10*—concrete

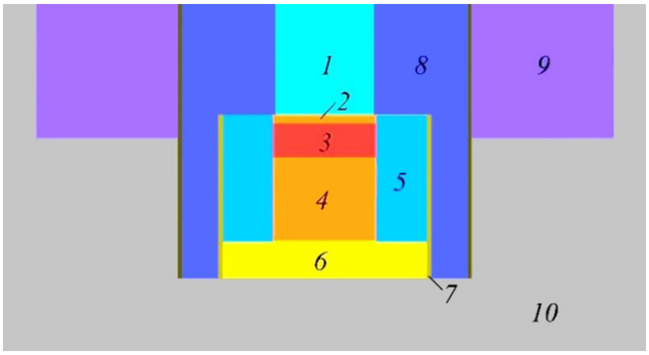
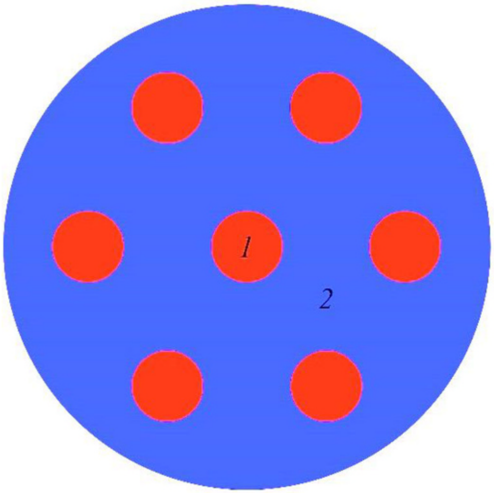


Fig. 3 Reactor whose main layouts are aimed at slowing down the kinetics: *1*—CPS column of a weakly neutron absorbing material; *2*—fuel rod and FA end caps; *3*—fuel; *4*—structures of fuel rods and FAs; *5*—side reflector of a weakly neutron absorbing material; *6*—support structures; *7*—shell; *8*—lead; *9*—pump chambers; *10*—concrete

elements, made of weakly neutron-absorbing materials, is minimized above the fuel part. If this condition is met and the neutron-absorbing structures above the core are excluded, it will be possible to achieve an average lifetime of more than 300 μs. In addition, if conditions for the weak absorption of migrating neutrons in the side reflector are created, the average lifetime will increase to about 500 μs. When the separating shell (lowering and lifting flows) of the reactor is made of a weakly absorbing neutron material in combination with the described measures, it will be possible to achieve an average neutron lifetime equal to ~1000 μs, i.e., to reach the required level of slowing down the kinetics. Such a layout is depicted in Fig. 3.

Although an average neutron lifetime of ~4000 μs in conventional layouts is almost impossible to achieve, is possible at more radical changes in the reactor layout, for example, when a multimodular core layout is used. This approach implies the division of the core into several modules of a quasi-cylindrical shape, for example, into seven: one module in the center and six on the periphery. An example of this layout is shown in Fig. 4. Although each module individually is deeply subcritical, together they form a critical system. The exchange of neutrons between the modules through a common reflector contributes to an increase in their average lifetime in the reactor. The average lifetime of neutrons in such a multimodular system with a 10- and 12-m reflector reaches 2500 and almost 4000 μs, respectively.

Fig. 4 Multimodular layout of the reactor: *1*—fuel part; *2*—lead and weakly neutron-absorbing elements



Conclusion

The nuclear safety of a fast lead-cooled reactor can be ensured by slowing down the kinetics due to migrating neutrons based on an increased level of self-protection. The kinetics is slowed down by creating the conditions in the neutron balance of fast neutron reactor fissions for a significant fraction of neutrons that have a long migration time in the reflector. The degree of slowing down the kinetics is determined by the average lifetime of neutrons in the reactor, which, under such conditions, is mainly determined by the lifetime of migrating neutrons. A degree of slowing down the kinetics corresponding to an average neutron lifetime of ~500 μs ensures the rapid insertion of the full reactivity margin at the minimum controlled power level to be withstood without dangerous consequences (maximum reactivity margin). This degree of slowing down the kinetics can be achieved while maintaining the dimensions of the reflector in the traditional reactor layout by implementing appropriate solutions that use a large weakly neutron-absorbing ^{208}Pb reflector and have structural elements made of weakly neutron-absorbing materials.

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