Peculiarities of the fast reactor with reflector from lead-208

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Abstract. Such specific properties of lead isotope $^{208}\text{Pb}$ as large atomic weight, weak neutron absorption and high-energy threshold of inelastic neutron scattering result can lead to some peculiarities in neutron kinetics of the fast reactor core reflected by a thick $^{208}\text{Pb}$-layer. These peculiarities are able to upgrade substantially the reactor safety by means of the following factors: additional delayed neutrons, “dead-time” of additional delayed neutrons, resistibility of the chain fission reaction against the reactivity jumps and some others considered in the paper.

1. Introduction

As is known [1], nuclear reactor kinetics is a relatively slow process only if the inserted reactivity is below effective fraction of delayed neutrons. In this case time-dependent behavior of the reactor power is defined by mean lifetime of delayed neutrons (0.3±80 s). If the inserted reactivity exceeds effective fraction of delayed neutrons, then nuclear reactor kinetics becomes very rapid process. In this case time-dependent behavior of the reactor power is defined by the substantially shorter value, namely mean lifetime of prompt neutrons. Mean prompt neutron lifetime covers the following ranges: ~0.1±1 μs in fast reactors and ~0.1±1 ms in thermal reactors. Just the use of light neutron moderators (light water, heavy water, graphite) provides the longer values (on 3–4 orders of magnitude) of mean neutron lifetime in thermal reactors as compared with analogous values in fast reactors. The longer mean neutron lifetime can slow down appropriately development of the chain fission reaction (CFR) on prompt neutrons.

Main purpose of the work is to find the ways for making fast reactor kinetics slower and, thus, for improving the reactor safety. These goals may be reached through neutrons slowing-down during their lengthy diffusion. However, application of light neutron moderators is an unacceptable option because of necessity to keep high-energy neutron spectrum in the reactor core. This contradictory and difficult problem may be solved only if fraction of the slowed neutrons is small while their lifetime is long. The first condition preserves high-energy neutron spectrum in the reactor core while the second condition elongates mean neutron lifetime. Both conditions can be satisfied by using heavy (in atomic weight) neutron moderators with weak neutron absorption.

The project of fast reactor BREST [2] supposes to use natural lead as a coolant and as a neutron reflector. Natural lead is characterized by intense inelastic neutron scattering in high-energy range and intense neutron absorption in low-energy range. Therefore, high-energy neutrons are actively slowed down and afterwards absorbed in the natural lead reflector. So, they can not return to the reactor core and contribute to the CFR development.
As is known, lead isotope $^{208}\text{Pb}$ is characterized by high-energy threshold of inelastic neutron scattering and weak ability of neutron absorption in low-energy range. So, $^{208}\text{Pb}$ is a weak moderator of high-energy neutrons and weak absorber of low-energy neutrons [3-6]. If lead isotope $^{208}\text{Pb}$ (or radiogenic lead with dominant content of $^{208}\text{Pb}$, or lead enriched with $^{208}\text{Pb}$) is substituted for natural lead as a neutron reflector, then the reactor core is surrounded by a physically thick material with large atomic weight and with better neutron reflection properties. Such a neutron reflector can return some part of neutron leakage into the reactor core after a certain time delay. This means that $^{208}\text{Pb}$-reflector can produce some additional delayed neutrons, which may be called as the delayed neutrons from the neutron reflector (briefly, the delayed reflector neutrons) in contrast with traditional delayed neutrons emitted by some fission products (briefly, the delayed FP-emitted neutrons). Appearance of additional delayed neutrons can produce a favorable effect on neutron kinetics of fast reactors and, thus, upgrade safety of fast reactor operation [7-8].

It should be noted that the processes of neutron slowing-down and transport of neutron pulses in physically thick systems containing heavy neutron moderators were thoroughly investigated in the 1940-50s, and the obtained results were presented in papers [9-10].

2. Neutron-physical properties of natural lead and lead isotope $^{208}\text{Pb}$

Natural lead consists of lead isotopes with relatively large atomic weights. Therefore, mean logarithmic energy loss at elastic neutron scattering by lead isotopes is very small, about 1% [11]. In addition, high-energy (above 1 MeV) neutrons, after elastic scattering by heavy nuclei, mainly keep the same, initial direction of their movement [12]. Both these factors allow high-energy neutrons going from the reactor core to penetrate deeply in the lead neutron reflector. High value of the first excitation level of $^{208}\text{Pb}$ nuclei results in the higher values of energy threshold for reaction of inelastic neutron scattering by $^{208}\text{Pb}$ as compared with analogous values of other lead isotopes (2.6 MeV for $^{208}\text{Pb}$ against 0.6-0.9 MeV for other lead isotopes [12]). So, isotope $^{208}\text{Pb}$ is a relatively weak moderator of high-energy neutrons, and they would be able to penetrate deeper in $^{208}\text{Pb}$-reflector.

$^{208}\text{Pb}$ nucleus is a double-magic nucleus with completely closed neutron and proton shells. Maybe, just this is a reason for the fact that, amongst all lead isotopes, $^{208}\text{Pb}$ is characterized by the lowest micro cross-sections of radiative neutron capture with resonances in high-energy range only [11]. The extremely weak ability of $^{208}\text{Pb}$ to absorb neutrons has the following consequences.

Firstly, in the reactor core reflected by $^{208}\text{Pb}$ probability for neutrons to be slowed down to thermal energies without absorption is very high (near to 100% [7-8]) in comparison with analogous value for the reactor core reflected by natural lead (about 30% only [7-8]).

Secondly, mean-root-square displacement of neutrons during their diffusion to $^{208}\text{Pb}$-reflector (near to 8 m [7-8]) is substantially longer than that for natural lead reflector (about 0.3 m only [11]). It should be noted here that mean-root-square displacement of neutrons during their moderation by natural lead from energies of fission neutrons to thermal energies (about 2 m [13]) slightly depends on lead isotope composition. As a consequence, the neutrons slowed by $^{208}\text{Pb}$-reflector down to thermal energies have a possibility to escape absorption and come back to the reactor core while, in the case of natural lead reflector, all these neutrons will be almost completely absorbed.

Thirdly, mean lifetime of thermal neutrons in natural lead is about 1 ms only [13], the same value in $^{208}\text{Pb}$ is substantially longer (about 0.6 s [7-8]). As is known, time of neutron moderation from energies of fission neutrons to thermal energies is rather short (several milliseconds) even in the heaviest materials [7-8, 11, 13-14]. As a result, $^{208}\text{Pb}$-reflector (in contrast to natural lead reflector) is able to return a considerable fraction of neutron leakage to the reactor core. The neutrons coming back from the neutron reflector will contribute to the CFR development after certain, maybe relatively lengthy time delay. Neutron kinetics will be slowed down with a favorable effect on the reactor safety. The mentioned above characteristics of other liquid-metal coolants (sodium, bismuth) are close to those of natural lead but they are inferior to those of $^{208}\text{Pb}$ [14-16].

Thus, neutron-physical peculiarities of $^{208}\text{Pb}$ can provoke appearance of some new CFR features valuable for kinetics of fast reactors.
3. The CFR features valuable for fast reactor kinetics
This section considers the CFR features in fast reactor with the reactor core surrounded by the neutron reflector made of heavy (in atomic weight) material with weak neutron absorption.

3.1 Additional delayed neutrons
The neutrons slowed down by the reflector material can come back to the reactor core and contribute to the CFR development as some kind of additional delayed neutrons. In essence, the reflector converts prompt fission neutrons leaking from the reactor core to those neutrons whose characteristics are very close to characteristics of the delayed FP-emitted neutrons. In fact, total fraction of delayed neutrons increases. So, conventional and additional delayed neutrons are generated by different physical processes, and the generation places are located in different reactor zones (in the reactor core and in neutron reflector). The principal condition for generation of additional delayed neutrons is the application of physically thick neutron reflectors. However, necessary amounts of $^{208}$Pb may be decreased by disposition of light materials behind $^{208}$Pb-reflector or by disposition of $^{208}$Pb-layer inside of the reactor core.

The contributions given by neutrons with different lifetimes to reactivity of fast BREST-type reactor, thermal VVER-type and CANDU-type reactors are shown in figure 1. The curves include the reactivity contributions given by prompt neutrons, the delayed FP-emitted neutrons and the delayed reflector neutrons of fast BREST-type reactor.

![Figure 1](image)

**Figure 1.** The contributions given by neutrons with different lifetimes to reactivity of fast and thermal reactors.

If the BREST reactor core is surrounded by natural lead reflector (0.5 m thick, as it is supposed by the BREST project [2]), then the neutron reflector can return some fraction of neutron leakage to the reactor core with considerable contribution to the reactor reactivity ($\approx 2\beta$, where $\beta$ - effective fraction of delayed neutrons). However, lifetime of the reflected neutrons is rather short ($\approx 1\mu$s) and slightly differs from neutron lifetime in the reactor core ($\approx 0.4\mu$s). The neutrons returned to the reactor core by the thicker (1.5 m) reflector contribute to the reactor reactivity about $4\beta$. Lifetime of the reflected neutrons is equal to $\approx 0.5\,\text{ms}$, near to prompt neutron lifetime in CANDU-type reactors, i.e. very short again. This can be caused by intense neutron absorption in natural lead. As a consequence, neutrons with long lifetime are not able to come back from remote points of neutron reflector to the reactor core, and these neutrons are completely absorbed by natural lead during their diffusion time.
Unfortunately, thickening of natural lead reflector can not produce considerable slowing-down effect on the CFR development.

The same words may be said about $^{208}$Pb-reflector, 1.5 m thick. The neutrons returned by such reflector to the reactor core can give rather large reactivity contribution (≈3-β), but their lifetime is below 1 ms, like neutron lifetime in thermal CANDU-type reactors. However, if $^{208}$Pb-reflector was thickened up to 2.5 m, then the neutrons returned by such reflector to the reactor core can give relatively small reactivity contribution (≈3-β), but their lifetime is sufficiently elongated up to 30 ms. This lifetime is significantly longer than neutron lifetime in CANDU-type reactors (≈1 ms) and approaches to the shortest lifetime of the delayed FP-emitted neutrons (≈0.3 s). Besides, the reactivity contribution given by the delayed reflector neutrons is 70 times larger than the reactivity contribution given by the delayed FP-emitted neutrons with the shortest lifetime. The delayed reflector neutrons are already able to slow down the CFR development. If $^{208}$Pb-reflector was more thickened, up to 4 m, then the neutrons returned by such reflector to the reactor core can give the smaller reactivity contribution (≈2-β), but their lifetime is elongated up to 0.1 s. If $^{208}$Pb-reflector was once more thickened, up to 6 m, then the neutrons returned by such reflector to the reactor core can give very small reactivity contribution (≈0.3-β), but their lifetime is elongated up to 0.3 s, i.e. up to the shortest lifetime of the delayed FP-emitted neutrons. Unfortunately, so thick neutron reflectors are unrealistic ones.

So, the delayed $^{208}$Pb-reflector neutrons in fast BREST-type reactor cover the range of time delays between prompt neutron lifetime and lifetime of the delayed FP-emitted neutrons, i.e. from fractions of microsecond to fractions of second. Reactivity contributions of the delayed reflector neutrons with the longest lifetime are comparable or even larger than those from the delayed FP-emitted neutrons. Lifetime of the delayed reflector neutrons is longer by several orders of magnitude than mean neutron lifetime in thermal reactors. So long neutron lifetime in fast BREST-type reactor with thick $^{208}$Pb-reflector opens an opportunity to slow down the CFR development and, thus, improve safety of the reactor operation.

3.2 “Dead-time” of additional delayed neutrons

As is known, the delayed FP-emitted neutrons, like prompt fission neutrons, begin contributing to the CFR development just after the fission reaction occurred, although their contributions are stretched in time. On the contrary, the delayed reflector neutrons are characterized by the certain “dead-time” during which they are deprived of a possibility to give any contribution to the CFR development. The “dead-time” is a sum of neutron diffusion times from the reactor core to the neutron reflector and back. This peculiarity of the delayed reflector neutrons can play a favorable role for safety of fast reactor operation.

3.3 The CFR resistibility against jump-like growth of heat generation rate

It can be shown that the CFR in fast BREST-type reactor with $^{208}$Pb-reflector is characterized by high resistibility against jump-like growth of heat generation rate. Thanks to the essentially increased fraction of delayed neutrons, even if the inserted positive reactivity exceeds fraction of the delayed FP-emitted neutrons, then the power excursion will occur not on prompt fission neutrons with extremely short mean lifetime but on the delayed reflector neutrons with substantially longer (by several orders of magnitude) mean lifetime. Naturally, the inserted positive reactivity must be lower that total fraction of the delayed FP-emitted neutrons and the delayed reflector neutrons. That is why the power excursion will be slowed down in time, without any jump-like bursts.

Dependencies of relative power growth rate at asymptotic power excursion on the inserted positive reactivity are presented in figure 2 for fast BREST-type reactor with two neutron reflectors (namely, natural lead, 0.5 m thick, and $^{208}$Pb, 4 m thick) and thermal CANDU-type reactor. As is seen, the power excursion in fast BREST-type reactor reflected by natural lead is characterized by jump-like burst of relative power growth rate (or jump-like shortage of asymptotic period) after insertion of positive reactivity at the level of fraction of the delayed FP-emitted neutrons. If reactivity increases
from 0.8$\beta$ to 1.2$\beta$, then the CFR speeds up by three orders of magnitude. If the same reactivity increment takes place in fast BREST-type reactor reflected by $^{208}$Pb and in thermal CANDU-type reactor, then the CFR speeds up by several times only. The CFR acceleration in fast BREST-type reactor is even weaker in comparison with CANDU-type reactor which, equally with RBMK-type reactor, is characterized by the slowest CFR development because of the longest mean neutron lifetime ($\sim$1 ms).

![Graph showing relative power growth rate as a function of reactivity]

**Figure 2.** Relative power growth rate as a function of the inserted positive reactivity for fast BREST-type reactor (two types of neutron reflector) and thermal CANDU-type reactor.

3.4 *Formation of additional delayed neutrons*

The delayed reflector neutrons, by their definition, are produced in neutron reflector. So, a principal possibility arises to form desirable spectrum of the delayed reflector neutron lifetimes and fractions by using various multi-layer reflectors. It seems appropriate to remind here that lifetimes and fractions of delayed neutrons are practically constants for all fissile nuclides, and it is impossible to change these values.

3.5 *Enhancement of Doppler-effect in the reactor core*

It seems possible to perform purposeful formation of resonance energy spectrum for neutrons coming back to the reactor core from neutron reflector. These resonance neutrons could increase the value of Doppler reactivity effect and, thus, upgrade safety of fast reactor operation.

3.6 *Impossibility of prompt super-criticality*

If control rods are placed in neutron reflector, then they can influence on reactivity by acting on the delayed reflector neutrons only. In this case prompt criticality of the reactor core remains unchanged. This is caused by existence of two principally different types of delayed neutrons, namely the delayed reflector neutrons and the delayed FP-emitted neutrons. Therefore, total reactivity worth of the control rods placed in neutron reflector is smaller than total fraction of delayed neutrons on effective fraction of the delayed FP-emitted neutrons. Therefore, if total reactivity worth of the control rods placed in the reactor core is smaller than total fraction of delayed neutrons, then prompt power excursion is impossible in such reactor, in principle. Naturally, this effect can upgrade safety of fast reactor operation.

3.7 *Neutron kinetics with variable characteristics of delayed neutrons*
If control rods are placed in neutron reflector, then the CFR kinetics is defined by variable fraction of delayed neutrons and variable neutron lifetime. As is known, similar feature is peculiar to molten-salt and gas-phase reactors [17], where fuel plays a role of coolant too, some fraction of liquid or gaseous fuel transfers thermal energy from the reactor core to heat exchanger. One important difference consists in the fact that only the delayed FP-emitted neutrons exist in such reactors. Therefore, total fraction of delayed neutrons in the reactor core is decreased. On the contrary, total fraction of delayed neutrons in fast BREST-type reactor is larger because it includes both fractions of the delayed FP-emitted neutrons and the delayed reflector neutrons.

3.8 Potential of neutron leakage
Natural lead is characterized by combination of two inherently contradictory properties. Large atomic weight results in weak neutron slowing-down and, as a consequence, in deep penetration of neutrons into reflector. However, intense absorption of the slowed neutrons does not allow them to come back to the reactor core. Significant neutron field can be formed in peripheral region of natural lead reflector. These neutrons are not able to come back to the reactor core and contribute to the CFR development. Numerical evaluations demonstrated that neutron leakage from natural lead reflector, 0.5 m and 1 m thick, had significant reactivity potentials: above 30-β and 20-β, respectively. Undoubtedly, so large potential of irretrievable neutron leakage should be profitably used. For example, fertile isotopes may be placed behind the reflector to produce fissile isotopes, or radioactive wastes (long-lived fission products and minor actinides) for their neutron transmutation.

3.9 Coupled system of two neutron-multiplying zones
Numerical evaluations demonstrated that neutron leakage from $^{208}$Pb-reflector, 2 m and 4 m thick, had significant reactivity potentials: above 22-β and 15-β, respectively. So, if annular neutron-multiplying layer is placed behind $^{208}$Pb-reflector, then the layer would be able to multiply the leaking neutrons, and some fraction of these neutrons could come back to the reactor core and, thus, increase fraction of delayed neutrons. In this case, the coupled system [18-21] is formed in the reactor that consists of the central reactor core with high-energy (fast) neutron spectrum and the peripheral neutron-multiplying layer with softened neutron spectrum. Just neutron leakage provides the system connectedness. The central reactor core is a sub-critical zone without the neutrons produced by the peripheral neutron-multiplying layer. Rate of the CFR development in the central reactor core is defined by relatively lengthy lifetime of neutrons coming back from the peripheral neutron-multiplying layer. Naturally, this effect can also upgrade safety of fast reactor operation.

3.10 Doppler-effect in annular neutron-multiplying layer
If $^{208}$Pb-reflector is surrounded by annular neutron-multiplying layer with low heat conductivity, and if resonance neutron spectrum is formed in the annular layer, then, in the case of neutron burst in the reactor core, the annular layer will rapidly warm-up and, thanks to Doppler-effect, absorption of the delayed reflector neutrons intensifies. But the reactor core becomes sub-critical if the delayed reflector neutrons are not able to come back to the reactor core. As a consequence, the CFR in the reactor core is slowed down, i.e. nuclear safety of the reactor core is improved.

3.11 Exclusion of back-end fuel cycle
Since neutron leakage from $^{208}$Pb-reflector is significant in value, it seems reasonable to place annular neutron-multiplying layer behind the reflector to form there resonance and epithermal neutron spectrum. Such a system of two coupled cores opens an opportunity for direct use of excessive neutrons leaking from the fast central core in the peripheral core with the softened neutron spectrum. So, it becomes real to use the secondary nuclear fuel produced in the peripheral core without any operations of back-end fuel cycle, i.e. without spent fuel reprocessing and re-fabrication of fresh fuel. Consequently, the coupled system of two cores will combine functions two reactors, with fast and thermal neutron spectra. However, the peripheral annular core has to apply technology of liquid-metal
coolant which is more complicated than traditional light-water coolant technology of VVER and PWR-type power reactors. Nevertheless, exclusion of back-end fuel cycle may be a very promising option. Similar idea was discussed in paper [18-21], where the following reactor design was proposed and analyzed: the central fast core was surrounded by layers of natural uranium (neutron reflector), beryllium moderator and high-density depleted uranium.

4. Conclusion
The paper demonstrated that neutron-physical properties of lead isotope $^{208}\text{Pb}$ resulted in some very promising peculiarities in neutron kinetics of the fast reactor cores surrounded by $^{208}\text{Pb}$-reflector. These peculiarities are able to upgrade substantially nuclear safety of fast lead-cooled reactors.

The listed advantages for safe operation of fast lead-cooled reactors can be also realized in the reactor with application of $^{208}\text{Pb}$ as a neutron reflector and radiogenic lead as a reactor coolant.

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**Acknowledgments**

The study was carried out in frame of the grant given by the Russian Science Foundation (Project No. 17-79-10334).