Improved safety fast reactor with “reservoir” for delayed neutrons generating

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Abstract. The paper considers the possibility to improve safety of fast reactors by using weak neutron absorber with large atomic weight as a material for external neutron reflector and for internal cavity in the reactor core (the neutron “reservoir”) where generation of some additional “delayed” neutron takes place. The effects produced by the external neutron reflector and the internal neutron “reservoir” on kinetic behavior of fast reactors are inter-compared. It is demonstrated that neutron kinetics of fast reactors with such external and internal zones becomes the quieter as compared with neutron kinetics of thermal reactors.

1. The in-hour equation and slowing down of fission chain reaction

Within the frames of one-point kinetic model with six groups of delayed neutrons (DN) without accounting for the reactivity feedbacks, the in-hour equation that links the asymptotic period of the runaway $T$ with the inserted positive reactivity $\rho$ may be written in the following form:

$$\rho = \frac{A_{\text{pr}i}}{T} + \sum_{i=1}^{6} \frac{A_i \cdot \beta_i}{T + A_i}$$

(1)

where: $\rho$ – the reactor reactivity, i.e. $\rho = (K_{\text{ef}} - K_0) \cdot (K_{\text{ef}} \cdot K_0)^{-1}$; $K_0, K_{\text{ef}}$ – the values of effective neutron multiplication factor in two different reactor states: the unperturbed state and the state perturbed by the reactivity insertion, respectively; $A_{\text{pr}i}$ – means prompt neutron lifetime in the reactors with traditional neutron reflectors; $A_i$ – means lifetime of nuclei-emitters of the $i$-th DN group ($A_i = 1/\lambda_i$, where $\lambda_i$ – decay constant of nuclei-emitters of the $i$-th DN group, $A_i = 0.3 \div 80$ s); $\beta_i$ – effective fraction of the $i$-th DN group; $\beta$ - effective DN fraction ($\beta = \sum_{i=1}^{6} \beta_i$).

It is desirable to slow down intensification of the fission chain reaction (FCR) in order to improve the reactor safety. The FCR deceleration means that the larger reactivity $\rho$ should be inserted into the reactor core to provoke the power excursion with the same asymptotic period $T$. As is seen from the in-hour equation (1), the FCR could be slowed down by elongating mean prompt neutron lifetime. The prompt neutron lifetimes in thermal reactors are longer than those in fast reactors by several orders of magnitude. If the fast reactor core is surrounded by a light neutron moderator, then the prompt neutron lifetime becomes longer, but the fast reactor is transformed into the reactor with thermal neutron spectrum. What should be done to elongate the prompt neutron lifetime and retain high-energy neutron spectrum of fast reactors?
2. The in-hour equation for fast reactor with weak neutron absorber as a neutron reflector

Mean prompt neutron lifetime can be elongated by using relatively intense neutron leakage from the reactor core. It is proposed to surround the reactor core by a low-absorbing neutron reflector where neutrons could stay as long as possible. Then, neutrons could come back to the reactor core and contribute into the FCR balance with a certain time delay, thus elongating mean lifetime of prompt neutrons. So, it is necessary to select such a reflecting material that allows neutrons to penetrate as deep as possible and then come back, with a high probability, to the reactor core. We propose to use lead enriched with isotope $^{208}\text{Pb}$ as a quite suitable material [1-5]. On the one hand, thanks to very low cross-section of neutron absorption by $^{208}\text{Pb}$ ($\sigma_c^{208}\text{Pb} = 0.23 \text{ mb}$), mean lifetime of thermal neutrons in infinite $^{208}\text{Pb}$ is equal to 0.6 s (this value may be considered as a typical delay time of neutrons in the $^{208}\text{Pb}$-reflector). On the other hand, heavy atomic weight of $^{208}\text{Pb}$ allows us to hope that neutrons coming back from the neutron reflector to the reactor core are mainly relatively high-energy neutrons, partially slow neutrons and thermal neutrons only as a minor fraction. So, the reactor could remain to be the fast spectrum reactor.

By analogy with delayed neutrons, the neutrons which are coming back from the neutron reflector may be divided into several groups each of them includes the neutrons coming from the $j$-th layer of the neutron reflector. Then, the following modified in-hour equation can be obtained with accounting for neutrons from the neutron reflector:

$$\rho = \frac{\Lambda_c}{T} + \sum_{j=1}^n \frac{\Lambda \cdot \beta}{T + \Lambda} + \sum_{j=1}^J \frac{A_j' \cdot \rho_j'}{T + A_j'}$$

where: $J$ – the number of spatial layers in the neutron reflector, $A_j'$ – lifetime of neutrons coming back from the $j$-th layer of the neutron reflector, this value is a sum of neutron lifetime in the reactor core before leakage into the neutron reflector, time needed to migrate from the reactor core to the $j$-th layer of the neutron reflector, time of staying in the $j$-th layer of the neutron reflector, time needed to migrate from the $j$-th layer of the neutron reflector to the reactor core and lifetime in the reactor core after coming back; $\rho_j'$ – the reactivity gain caused by surrounding the reactor core with the $j$-th layer of the neutron reflector: $\rho_j' = (K_j - 1) \cdot (K_j - 1)^{-1}$, $K_j$ – effective neutron multiplication factor in the reactor with $j$ layers of the neutron reflector. For brevity, this value may be called as the reflector reactivity.

It is noteworthy here that the first summand in the in-hour equation (1) includes prompt neutron lifetime $\Lambda_{prt}$ in the reactor as a whole. As distinct to equation (1), the first summand in the modified in-hour equation (2) includes neutron lifetime in the unreflected reactor core $\Lambda_c$.

If the number of spatial layers tends to infinity, then the discrete form of the in-hour equation (2) transforms into its continuous analog:

$$\rho = \frac{\Lambda_c}{T} + \sum_{j=1}^n \frac{\Lambda \cdot \beta}{T + \Lambda} + \int_0^V \frac{d\rho_{pr}(r)/dv \cdot A_c(r) \cdot dv}{T + A_c(r)}$$

where: $V$ – volume of the neutron reflector; $d\rho_{pr}(r)/dv$ – spatial distribution of the specific reactivity gain caused by the neutron reflector, $A_c(r)$ – spatial lifetime distribution for neutrons from the neutron reflector.

3. Fast reactors with different neutron reflectors

The paper considers three variants of the neutron reflectors in fast lead-cooled reactor BREST: the external neutron reflector made of natural lead (50-cm thick), the external neutron reflector made of $^{208}\text{Pb}$ (250-cm thick), the internal neutron reflector (the neutron “reservoir”, 250-cm thick) made of $^{208}\text{Pb}$. The internal neutron “reservoir” occupies central zone of the reactor core, i.e. the neutron “reservoir” is encircled all round by the reactor core. For simplicity, initial cylindrical models were replaced by equivalent spherical models (see Fig. 1.a, b, c). Initial cylindrical model of the fast reactor core with the internal neutron “reservoir” is presented in Fig. 1.d. Thicknesses of the reactor core and fuel enrichments were chosen by such a way that the reactors would be critical and their breeding ratio
would be about 1.05, as in initial model. This means that neutron-physical parameters of the fast reactors with the external and internal neutron reflectors made of $^{208}\text{Pb}$ would be close to the reactors reflected by natural lead.

![Diagram](image)

**Figure 1.** Spherical (a, b, c) and cylindrical (d) models of fast BREST-type reactor.

4. **Lifetime and reactivity of neutrons from the neutron reflector**

Lifetime of neutrons from the neutron reflector can be calculated by using the balance relationship presented in [3]. For the discrete model of the neutron reflector the balance relationship can be written in the following form: 

$$
A_{\text{pr}+1}^{j} = (1 - \rho_{R}^{j}) \cdot A_{\text{pr}+1}^{j-1} + \rho_{R}^{j} \cdot A_{\text{pr}}^{j} ,
$$

where $A_{\text{pr}}^{j}$ – prompt neutron lifetime in the reactor with $j$ layers of the neutron reflector, if $j=0$, then $A_{\text{pr}+1}^{0} = A_{\text{pr}}^{0} \cdot \rho_{R}^{0}$ – neutron lifetime in the unreflected reactor core. For the continuous model of the neutron reflector the balance relationship can be rewritten as follows:

$$
A_{\text{pr}+1}^{j} = A_{\text{pr}+1}^{j-1} + \frac{A_{\text{pr}}^{j}}{\rho_{R}^{j}}.
$$

Some dependencies of relevant physical parameters on thickness of $^{208}\text{Pb}$-reflector are presented in Fig. 2 for fast BREST-type reactor. These dependencies were calculated within the frames of spherical continuous model of neutron kinetics. It can be seen that the reactivity gain thanks to the reflector $\rho_{R}(r)$ grows as the reflector becomes thicker and approaches a saturation level. The term “thickening of the internal reflector” means increment of the reflector thickness from the inner boundary of the annular reactor core to the reactor center.
Those neutrons which are coming back to the reactor core from the deeper layers of the neutron reflector are characterized by the longer lifetime. But the number of these neutrons gradually decreases and, as a result, their contribution into the FCR balance decreases too. As is shown in Fig. 2, the neutrons coming from the external reflector and from the neutron “reservoir” ($^{208}$Pb, 250-cm thick) are able to provide significant total contribution into the reactivity, at the level of $15 \beta$ and $100 \beta$, respectively. Lifetimes of these neutrons cover the range from 0.3 μs to 0.02 s and 0.08 s, respectively.

5. Asymptotic process of behavior of fast and thermal reactors

Dependencies of the reactivity required to provoke the power excursion with the asymptotic period T are presented in Fig. 3 for the following cases: fast BREST-type reactor with the external reflectors made of natural lead (50-cm thick) and made of $^{208}$Pb (250-cm thick); fast BREST-type reactor with the internal reflector (neutron “reservoir”) made of $^{208}$Pb (250-cm thick); thermal VVER-type reactor and thermal CANDU-type reactor. As is seen, fast BREST-type reactor reflected by natural lead (50-cm thick) is characterized by rather short prompt neutron lifetime (about 1 μs) and, as a consequence, the most rapid and the most dangerous neutron kinetics – the rapid power excursions can be provoked by relatively small reactivities. Neutron kinetics of fast BREST-type reactor reflected by $^{208}$Pb at the power excursions with the asymptotic periods shorter than 0.01 s is comparable with neutron kinetics of thermal VVER-type reactor with prompt neutron lifetimes at the level of 0.1 ms. Fast BREST-type reactor with the internal reflector (neutron “reservoir”) made of $^{208}$Pb is characterized by even the quieter neutron kinetics than thermal CANDU-type reactor with the longest prompt neutron lifetimes (at the level of 1 ms).
6. Transitional process of behavior of fast and thermal reactors

Time-dependent power evolutions are presented in Fig. 4 for the reactors mentioned above just after the positive reactivity jump (+0.9 $\beta$), i.e. before establishing the asymptotic power evolution.

Figure 3. Dependencies of the required reactivity $\rho$ on the asymptotic period of runaway $T$ for BREST-type with different reflectors as well as VVER-type and CANDU-type reactors.

Figure 4. Reactor power as functions of time after reactivity insertion for fast BREST-type reactor with different reflectors as well as VVER-type and CANDU-type reactors.

“BREST” – BREST-type reactor with 0.5 m natural lead external reflector (Fig. 1a),

“BREST-ex” – BREST-type reactor with 2.5 m $^{208}$Pb external reflector (Fig. 1b),

“BREST-in” – BREST-type reactor with 2.5 m $^{208}$Pb internal reflector (“reservoir”) and 1.5 m natural lead external reflector (Fig. 1c, d).
As is seen (Fig. 4), power of fast BREST-type reactor reflected by natural lead (50-cm thick) increases on one order of magnitude instantly, for 10 ms after the reactivity jumped. The same power excursions occurred in thermal VVER-type reactor and CANDU-type reactor for substantially longer time intervals (0.4 s and 2 s, respectively). The same power excursions in fast BREST-type reactor with the external reflector can occur for one second, with the external and internal reflectors – for four seconds. So long power evolutions can produce a favorable effect on the reactor safety because negative reactivity feedbacks on coolant properties can receive enough time to actuate.

7. Conclusions
1. The way is proposed to decelerate neutron kinetics of fast reactors and, thus, improve the reactor safety by using $^{208}\text{Pb}$ as a material of the external neutron reflector and as a material of the internal neutron reflector (the neutron “reservoir” inside of the reactor core).
2. The neutron “reservoir” is more effective than the external reflector because neutrons from the “reservoir” are not lost for the FCR, they come back to the reactor core inevitably. On the contrary, significant neutron fraction can pass through the external reflector and become useless for the FCR.
3. After positive reactivity jump, power of fast BREST-type reactor with the external and internal neutron reflectors made of $^{208}\text{Pb}$ increases substantially slower than power of thermal VVER-type reactor and CANDU-type reactor in transient and asymptotic processes.

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