Nuclear safety of the fast reactor with $^{208}$Pb-reflector at neutron flash above effective fraction of delayed neutrons

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Abstract. This paper aims at improving fast reactors safety through slowing-down their power runaways. The method is surrounding the core by the neutron reflector made of materials of heavy atomic weight and extremely low neutron absorption. The power runaways can be slowed down because of a long way for leakage neutrons to come back from distant layers of neutron reflector to the core. Time interval needed for leakage neutrons to come back to the core could become comparable with lifetime of delayed neutrons. So, this kind of reflector is able to transform some fraction of prompt leakage neutrons into additional group of delayed neutrons. It has been demonstrated that mean prompt neutron lifetime can be elongated roughly by three orders of magnitude with appropriate slowing-down the reactor power runaway. The most significant slowing-down the power runaways can be reached at the most dangerous reactivity insertion, i.e. at the reactivity larger than effective fraction of delayed neutrons. Thanks to the elongated mean prompt neutron lifetime and to the shortened time constant of fuel rods the negative consequences of the accidental reactivity insertion above effective fraction of delayed neutrons could be substantially weakened because, in addition to the Doppler-effect, the negative feedbacks on coolant and cladding temperatures receive enough time to actuate.

1. Introduction

As it was shown in publications [1-5], if fast reactor core is surrounded by the neutron reflector made of heavy and weak neutron-absorbing material, then the CFR can be remarkably slowed down and, as a consequence, the reactor safety can be upgraded. The neutron reflector may be made, for example, of the lead with increased content of its heaviest isotope $^{208}$Pb. The CFR deceleration can be explained by deep penetration of fast fission neutrons from the reactor core into the neutron reflector, by neutron moderation in the reflector and, mainly, by lengthy return of slow neutrons from the neutron reflector to the reactor core. Fraction of fast fission neutrons leaking from the reactor core into the neutron reflector can be substantially larger than effective fraction of delayed neutrons $\beta$.

So, the neutrons coming from the neutron reflector can participate in the CFR propagation only after a long time delay. It is important to use heavy and weak neutron-absorbing material in the neutron reflector because of the following two reasons. Firstly, the neutron reflector made of light material can transform fast neutron spectrum into thermal one. Secondly, the neutron reflector made of strong neutron absorber does not allow neutrons to return from the reflector to the reactor core. The latter effect takes place in the fast BREST-type reactor core reflected by natural lead [6].
2. Kinetics of transients
Multi-point mathematical model of neutron kinetics in the fast reactor with physically thick reflector used below is described in appendix. If positive reactivity $\rho = 0.5\beta$ (see figure 1) was inserted into the reactor core reflected by natural lead, then, according to the neutron kinetics theory, the reactor power quickly jumps on prompt neutrons and increases by a factor of $[\beta/(\beta-\rho)]$, i.e. twice. Afterwards, the further growth of the reactor power is mainly defined by delayed neutrons, and the reactor power increases exponentially with asymptotic period about 5.7 s.

If the same positive reactivity $\rho = 0.5\beta$ was inserted into the reactor core reflected by $^{208}$Pb, then the reactor power grows up very slowly and increases twice only in a second. Afterwards, the reactor power increases with relatively slower rate, with asymptotic period about 7.2 s. This effect can be explained as follows. The neutron reflector made of $^{208}$Pb returns neutrons to the reactor core with a certain time delay, and the time delay can cover the range from prompt neutron lifetime to delayed neutron lifetime. In addition, the neutrons coming back from the reflector can contribute several dozens of $\beta$ to the reactor criticality. Thus, the “delayed neutron” concept itself loses the sense. Consequently, the reactor is a deeply subcritical system on prompt neutrons which did not escape the reactor core, and the reactor power increases thanks to the neutrons coming back from the reflector only.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Fast reactor power after insertion of positive reactivity $\rho = 0.5\beta$.

If the larger positive reactivity $\rho = 2\beta$ (see figure 2) was inserted into the reactor core reflected by natural lead, then the reactor becomes supercritical on prompt neutrons. In this case, the reactor power increases very quickly with asymptotic period about 0.13 ms that is defined by prompt neutron lifetime.
Figure 2. Fast reactor power after insertion of positive reactivity $\rho = 2.0\beta$.

The reactor core reflected by $^{208}\text{Pb}$ is a deeply subcritical system, if the neutrons coming back from the reflector do not contribute into the CFR propagation. Therefore, the reactor power increases substantially slower just after the reactivity insertion and after establishment of asymptotic period at the level about 0.23 s that is 2000 times longer than asymptotic period in the reactor core reflected by natural lead as seen in figure 2.

So, the neutron reflector made of $^{208}\text{Pb}$, can substantially decelerate kinetic behavior of the fast reactor under accidental insertion of positive reactivity which can be larger and lower than effective fraction of delayed neutrons.

3. Neutron flash

According to the neutron flash model [7], if the positive reactivity above $\beta$ was inserted into the reactor core, then heat removal from fuel by coolant and effects produced by delayed neutrons can be neglected because the positive reactivity provoked a very rapid process. Only prompt Doppler-effect has enough time to actuate as a negative reactivity feedback. Full energy yield that releases during the neutron flash is defined by the product of maximal achievable power and duration of the neutron flash. However, duration of the neutron flash is directly proportional to mean neutron lifetime while maximal achievable power is inversely proportional to mean neutron lifetime. As a result, full energy yield of the neutron flash is independent on mean neutron lifetime.

Kinetic behavior of the fast BREST-type reactor can be decelerated by surrounding the reactor core with the neutron reflector made of $^{208}\text{Pb}$. The $^{208}\text{Pb}$-neutron reflector (four meters thick) can elongate mean neutron lifetime by three orders of magnitude. As the consequences, maximal achievable power decreases and duration of the neutron flash increases by three orders of magnitude. Such a relatively slow process can be easily modeled, and full energy yield can be evaluated more correctly. Maximal pressure in fuel rods induced by expansion of materials at the reactivity jump is inversely proportional to the squared mean neutron lifetime [7]. That is why the neutron reflector made of $^{208}\text{Pb}$ is able to reduce drastically such a dangerous pressure.

Besides, during the prolonged neutron flash some heat fraction has enough time to flow down to coolant, i.e. fuel rod stops being closed for heat removal. So, the reactor becomes able to overcome the neutron flash with minimal negative consequences.

If additional negative reactivity feedback on coolant temperature could be actuated, then just this feedback would work in the first turn under conditions of effective heat removal from fuel by coolant. If the reactivity effect produced by increased temperature of coolant is insufficient, then Doppler-
effect can display its action. If the neutron reflector is made of $^{208}$Pb, the value of Doppler-effect is larger than that in the reactor core reflected by natural lead because of the following reason. The neutrons coming back from $^{208}$Pb-reflector are characterized by the softer neutron spectrum than the neutrons coming back from natural lead. As is known, the softer neutron spectrum in the resonance range can produce the larger Doppler-effect. Besides, Doppler-effect begins acting not immediately, as in the case of the neutron reflector made of natural lead, but the Doppler-effect action is stretched in time.

Thermal power of the reactor core reflected by natural lead will fly up over the nominal value (700 MW) on several orders of magnitude for some milliseconds (see figure 3). This means that rate of continuous heat removal from fuel by coolant is negligibly small in comparison with heat generation rate in the neutron flash, and fuel will strongly warm up during some milliseconds (see figure 4).

**Figure 3.** Fast reactor power at the neutron flash.

**Figure 4.** Fuel temperature in fast reactor at the neutron flash.
Thermal power of the reactor core reflected by $^{208}\text{Pb}$ (figure 3) will increase up over the nominal value (700 MW) moderately, the growth will be smaller by several orders of magnitude, thermal power will begin growing with a significant time delay, and duration of the neutron flash will be longer on several orders of magnitude. This means that rate of continuous heat removal from fuel by coolant is comparable with heat generation rate in the neutron flash. Fuel will start warming up with a certain time delay, and fuel temperature will increase on relatively smaller value (figure 4). So, the reactor will be able to overcome the neutron flash with minimal negative effects.

Finally, if fuel rods with sufficiently short time constant [8] that can provide safe and reliable heat removal from fuel rods by coolant at the utmost possible reactivity jump without scram are used in the fast BREST-type reactor, then the reactor is able to overcome any possible reactivity jumps thanks to the only one negative reactivity feedback on coolant temperature, even without actuation of Doppler-effect. Such reactor may be called as an inherently safe reactor.

### 4. Natural resources of radiogenic lead

In nature there are two types of elemental lead with substantially different contents of four stable lead isotopes ($^{204}\text{Pb}$, $^{206}\text{Pb}$, $^{207}\text{Pb}$, and $^{208}\text{Pb}$). The first type is a natural, or common, lead with a constant isotopic composition (1.4% $^{204}\text{Pb}$, 24.1% $^{206}\text{Pb}$, 22.1% $^{207}\text{Pb}$, and 52.4% $^{208}\text{Pb}$). The second type is a so-called radiogenic lead with very variable isotopic composition. Radiogenic lead is a final product of radioactive decay chains in uranium and thorium ores. That is why isotopic compositions of radiogenic lead are defined by the ore age and by elemental compositions of mixed thorium-uranium ores sometimes with admixture of natural (common) lead as an impurity. The isotopes $^{206}\text{Pb}$, $^{208}\text{Pb}$, and $^{207}\text{Pb}$ are the final products of the radioactive decay chains starting from $^{232}\text{Th}$, $^{238}\text{U}$, and $^{235}\text{U}$, respectively:

$$
^{232}\text{Th} \rightarrow 6\alpha+4\beta (14.6-10^9 \text{ years}) \rightarrow ^{208}\text{Pb}, \\
^{238}\text{U} \rightarrow 8\alpha+6\beta (4.6-10^9 \text{ years}) \rightarrow ^{206}\text{Pb}, \\
^{235}\text{U} \rightarrow 7\alpha+4\beta (0.7-10^9 \text{ years}) \rightarrow ^{207}\text{Pb}.
$$

Therefore, radiogenic lead with large abundance of $^{208}\text{Pb}$ could be extracted from natural thorium and thorium-uranium ores [9-13] without any isotope separation procedures.

It should be noted that neutron capture cross-sections of $^{206}\text{Pb}$, although larger than those of $^{208}\text{Pb}$, are significantly smaller than those of $^{207}\text{Pb}$ and $^{208}\text{Pb}$. Thus, at first glance it appears that the ores containing ~93% $^{208}\text{Pb}$ and 6% $^{206}\text{Pb}$ (Table 1) could provide the necessary composition of radiogenic lead. However, the first estimations showed that the content of only 1% $^{204}\text{Pb}$ and $^{207}\text{Pb}$ (these isotopes have high values of capture cross-sections) in radiogenic lead could significantly weaken the advantages of radiogenic lead in thermal nuclear reactors.

| Table 1. Main deposits of uranium, thorium and mixed uranium-thorium ores. |  |
| --- | --- | --- |
| Ore deposits | U / Th / Pb [weight %] | $^{204}\text{Pb}/^{206}\text{Pb}/^{207}\text{Pb}/^{208}\text{Pb}$ [atomic %] |
| Guarapari, Brazil | 1.3 / 59.3 / 1.5 | 0.005 / 6.03 / 0.46 / 93.5 |
| Manitoba, Canada | 0.3 / 15.6 / 1.5 | 0.010 / 10.2 / 1.86 / 87.9 |
| Mt. Isa Mine, Australia | 0.0 / 5.73 / 0.3 | 0.038 / 5.44 / 0.97 / 93.6 |
| Las Vegas, USA | 0.1 / 9.39 / 0.4 | 0.025 / 9.07 / 1.13 / 89.8 |
| South Bug, Ukraine | 0.2 / 8.72 / 0.9 | 0.010 / 6.04 / 0.94 / 93.0 |
| “Common” lead | | 1.4 / 24.1 / 22.1 / 52.4 |

So, radiogenic lead can be taken as a by-product from the process of uranium and thorium ores mining. Until now, extraction of uranium or thorium from minerals had been followed by throwing radiogenic lead into tail repositories. If further studies will reveal the perspective for application of radiogenic lead in nuclear power industry, then a necessity arises to arrange by-extraction of...
radiogenic lead from thorium and uranium deposits or tails. Evidently, the scope of the ores mining and processing is defined by the demands for uranium and thorium.

However, the demands of nuclear power industry for thorium are quite small now and will remain so in the near future. Nevertheless, there is one important factor that can produce a substantial effect on the scope of thorium and mixed thorium-uranium ore mining. In the majority of cases, uranium and thorium ores belong to the complex-ore category, i.e., they contain minor amounts of many valuable metals (rare-earth elements, gold and so on).

The paper by Sinev [14] has demonstrated that the presence of useful accompanying elements (some elements of cerium group, in particular) in uranium and thorium ores might be a factor of high significance for making cheaper the process of natural uranium and thorium production. By-extraction of some valuable elements from uranium ores can drop the smaller limit (industrial minimum) of uranium content in ores to 0.01% to 0.03% under application of the existing technologies for natural uranium extraction. Radiogenic lead can be recovered from the available tail repositories or as a by-product of the processes applied for extraction of the accompanying valuable metals from uranium and thorium ores [15].

5. Conclusion
The paper proposes a way towards upgrading the fast reactor safety by slowing-down the reactor kinetics. Kinetic behavior of the fast reactor can be decelerated by surrounding the reactor core with the neutron reflector made of $^{208}$Pb. The deceleration effects were evaluated for two cases: 1. no feedbacks were taken into consideration; 2. the negative feedback related with Doppler-effect was taken into account.

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