Research Article

On a significant slowing-down of the kinetics of fast transient processes in a fast reactor[*]

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Abstract

The kinetics of nuclear reactors is determined by the average neutron lifetime. When the inserted reactivity is more than the effective delayed neutron fraction, the reactor kinetics becomes very rapid. It is possible to slow down the fast reactor kinetics by increasing the neutron lifetime. The authors consider the possibility of using the lead isotope, ^{208}Pb, as a neutron reflector with specific properties in a lead-cooled fast reactor. To analyze the emerging effects in a reactor of this type, a point kinetics model was selected, which takes into account neutrons returning from the ^{208}Pb reflector to the reactor core.

Such specific properties of ^{208}Pb as the high atomic weight and weak neutron absorption allow neutrons from the reactor core to penetrate deeply into the ^{208}Pb reflector, slow down in it, and have a noticeable probability to return to the reactor core and affect the chain fission reaction. The neutrons coming back from the ^{208}Pb reflector have a long 'dead-time', i.e., the sum of times when neutrons leave the reactor core, entering the ^{208}Pb reflector, and then diffuse back into the reactor core. During the 'dead-time', these neutrons cannot affect the chain fission reaction. In terms of the delay time, the neutrons returning from the deep layers of the ^{208}Pb reflector are close to the delayed neutrons. Moreover, the number of the neutrons coming back from the ^{208}Pb reflector considerably exceeds the number of the delayed neutrons.

As a result, the neutron lifetime formed by the prompt neutron lifetime and the 'dead-time' of the neutrons from the ^{208}Pb reflector can be substantially increased. This will lead to a longer reactor acceleration period, which will mitigate the effects of prompt supercriticality. Thus, the use of ^{208}Pb as a neutron reflector can significantly improve the fast reactor nuclear safety.

Keywords

Kinetics, fast reactor, reflectors based on natural lead and lead-208, VVER and CANDU thermal reactors, fission chain reaction, transient process, asymptotic acceleration

Introduction

It is shown in (Shmelev et al. 2011, 2013, Kulikov et al. 2014, 2017a, b, c, d, Kulikov 2017) that the use in a fast reactor of a physically thick reflector about 4 m thick made of lead-208 instead of a reflector made of natural lead 0.5 m thick makes it possible to radically slow down the development of a fission chain reaction. This is due
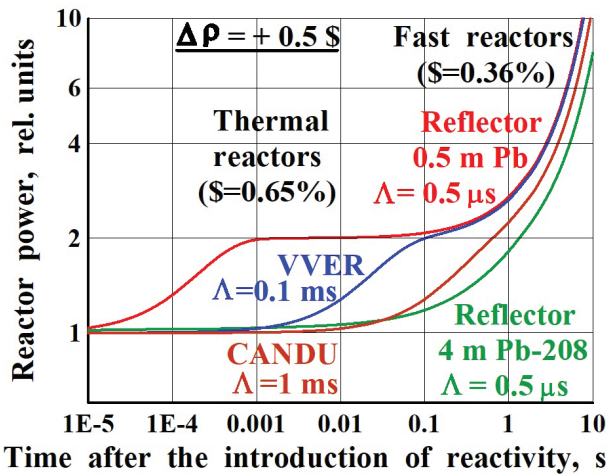
Figure 1. Change in the power of various reactors depending on the time after the introduction of reactivity +0.5 $.
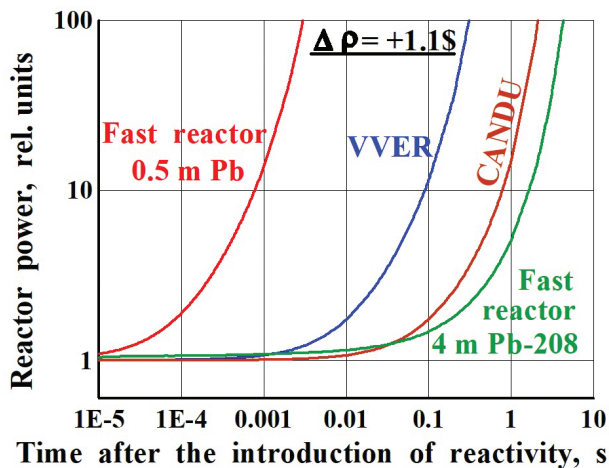

Figure 2. Change in the power of various reactors depending on the time after the introduction of reactivity +1.1 $.

to the long return of neutrons to the core from a reflector made of lead-208 due to its heavy atomic weight and low neutron absorption. As a result, the average neutron lifetime in such a reactor is about three orders of magnitude longer than in a reactor with a natural lead reflector. In the event of an unauthorized insertion of positive reactivity, the reactor power growth slows down and the amount of released energy in a reactivity accident decreases, which should improve its nuclear safety. The physical features of the formation and development of a fission chain reaction in a reactor of this type are considered in (Kulikov et al. 2018a, b, c, d).

An analysis of fast reactors with both reflector types was carried out. Their main characteristics are given in Table 1. The effective delayed neutron fraction is taken equal to 0.36%, i.e., the same as for plutonium fuel.

For comparison, the most widespread thermal reactors – VVER and CANDU – are considered under the same conditions. For them, the effective delayed neutron fraction is taken equal to 0.36%, i.e., the same as for uranium fuel. The average neutron lifetime in these reactors differs by

Table 1. Characteristics of reactors and their asymptotic acceleration periods (T_{ac})at different introduced reactivity.

Reactor	Reflector (thickness, material)	Effective delayed neutron fraction $, %	Average neutron lifetime, ms	Reactivity, $	
				+0.5	+1.1
				T_{ac}, s	
BREST	0.5 m, Pb	0.36	0.0005	5.72	0.00128
VVER	–	0.65	0.1	5.80	0.11
CANDU	–	0.65	1.0	6.50	0.61
BREST	4 m, Pb-208	0.36	+0.5	7.61	1.15

about an order of magnitude, i.e., 0.1 and 1 ms, respectively. Note that in a domestic thermal reactor of the RBMK type, the lifetime is comparable to that of CANDU.

The kinetics in the transient process and during the asymptotic acceleration of thermal reactors was calculated within the point model (Bell and Glasstone 1970, Bekurtz and Wirtz 1968) taking into account six groups of delayed neutrons, and for a fast reactor – using multipoint kinetics. In this case, one point fell on the core with delayed neutrons, and the other points – on each reflector layer 0.5 m thick (Shmelev et al. 2011). The kinetic parameters (the fraction and time of neutron return from the reflector through its layers) were estimated using TIME26, a one-dimensional 26-group program for calculating fast reactors (Apse and Shmelev 2008), within the framework of spherical geometry.

Features of power growth and energy release in the transient reactor acceleration process

Figs 1, 2 show the change in the power of a fast reactor surrounded by a 0.5 m thick reflector made of natural lead and a 4 m thick reflector made of lead-208, as well as thermal reactors of the VVER and CANDU types, depending on the time after the insertion of positive reactivities of 0.5 and 1.1 $, respectively.

It can be seen that at a reactivity of $ 0.5 in a fast reactor with a reflector made of natural lead, an almost instantaneous (in about 1 ms) double power leap occurs. It is associated with an improvement in the conditions for neutron multiplication and occurs due to the multiplication of prompt neutrons, the lifetime of which is short (about 0.4 μs). However, there is practically no further power growth until a time instant of about 0.1 s. This is due to the fact that the reactor remains subcritical on prompt neutrons. Therefore, its acceleration requires also delayed neutrons, the contribution of which to the fission chain reaction begins to appear after about 0.1 s, since this corresponds to the lifetime of the shortest-lived group of delayed neutrons. A further power growth occurs with the simultaneous participation of both prompt and delayed neutrons with an asymptotic period of 5.72 s in developing the chain fission reaction (see Table 1). All this corresponds to the well-known model of kinetics without feedback (Bell and Glasstone 1970, Bekurtz and Wirtz 1968).

In a VVER-type reactor, a similar change in power occurs with the only difference that the average prompt neutron lifetime is about two orders of magnitude longer than in a fast reactor. Therefore, a double power leap is observed after the reactivity is inserted (after about 0.1 s). Immediately thereafter, delayed neutrons begin to contribute to the fission chain reaction. In this regard, the section of the plateau in power depending on the time after introduction of reactivity is weakly expressed.

In a CANDU-type reactor, the leap in prompt neutron power occurs even later (after about 0.8 s), and the plateau section is absent, since the average lifetime of prompt neutrons is still an order of magnitude closer to the lifetime of delayed neutrons.

In a fast reactor with a lead-208 reflector, the power leap is completely absent, since the lifetime of neutrons returning from the reflector to the core corresponds to a wide range of values from the lifetime of prompt neutrons in the core (for neutrons returning from the first layers of the reflector) to the lifetime of delayed neutrons (for neutrons that return from the depth of the reflector), and the fraction of neutrons in the reflector is large (about $ 35). Table 1 shows that, although the asymptotic acceleration period gradually increases from reactor to reactor, this increase is insignificant.

The picture changes dramatically when a positive reactivity of +1.1 $ is inserted, which exceeds the effective delayed neutron fraction (Fig. 2). The reactors become supercritical on prompt neutrons, the average lifetime of which is significantly shorter than that of delayed neutrons; therefore, the power grows much faster with clearly shorter asymptotic acceleration periods (see Table 1), which radically differ in magnitude for different reactors. Thus, the asymptotic acceleration period for a fast reactor with a natural lead reflector is approximately 1 ms and, with a lead-208 reflector, it is almost three orders of magnitude longer. For thermal reactors, the asymptotic acceleration periods are intermediate values and, in a CANDU-type reactor, it is several times longer than in a VVER-type reactor, since the average prompt neutron lifetime in CANDU is about an order of magnitude longer than in VVER (see Table 1).

However, as is known, in reactivity accidents, damage to core elements can be caused not only by a power leap but also by the amount of energy released in this element. Figs 3, 4 show the amount of excess energy, i.e. the energy that does not have time to be removed under the condition of normal heat removal in different reactors from the time after the introduction of positive reactivity of 0.5 and 1.1 $, respectively. It is assumed that excess energy is released when the reactor power exceeds its rated value. Excess energy is measured in relative units as the product of the rated power and time. Thus, for example, excess power equal to 10 relative units means that energy was released in the fuel, and it was not removed to the coolant; this energy is generated in a reactor operating at a tenfold increase in the rated power for 1 s, or a fivefold increase in the rated power for 2 s, etc.
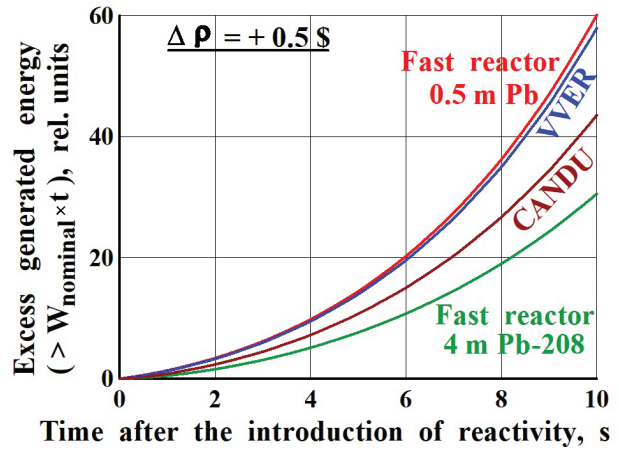

Figure 3. The amount of excess (not removed from the fuel) energy in various reactors versus time after the introduction of reactivity +0.5 $.
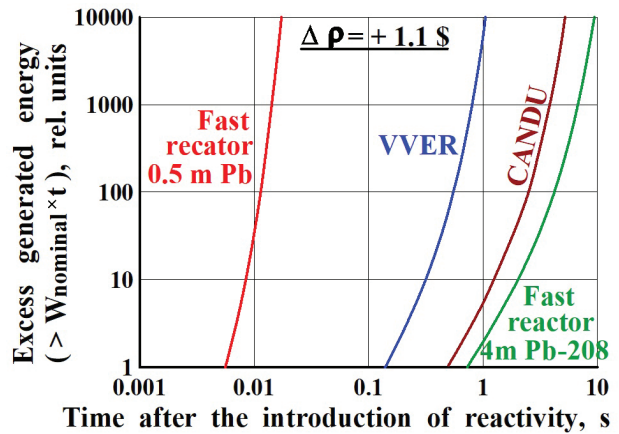

Figure 4. The amount of excess (not removed from the fuel) energy in various reactors versus time after the introduction of reactivity +1.1 $.

Fig. 3 shows that, at inserted positive reactivity of 0.5 $, the amount of energy not removed from the fuel in a fast reactor with a lead-208 reflector is approximately two times less than with a natural lead reflector at any time after the insertion of reactivity. In this sense, a VVER-type reactor is close to a fast reactor with a natural lead reflector, and CANDU occupies an intermediate position between fast reactors with different reflectors. It is obviously due to the corresponding asymptotic reactor acceleration periods (see Table 1). Thus, the rate of generation of excess energy does not differ too much in different reactors, since the acceleration process in them occurs mainly on delayed neutrons, the lifetime of which weakly depends on fuel types.

However, the rate of generation of excess energy differs sharply in reactors when positive reactivity is inserted that exceeds the effective delayed neutron fraction. As Fig. 4 shows, the same value (for example, 100 relative units) of excess energy in different reactors (fast reactor with a natural lead reflector, VVER, CANDU, fast reactor with a lead-208 reflector) is reached for significantly

different times (0.0114, 0.55, 2.5 and 4.2 s, respectively). This is due to significantly different asymptotic reactor acceleration periods (see Table 1). The asymptotic periods are determined by the absence of long-lived neutrons in a natural lead reflector in a fast reactor, the presence of comparatively longer-lived prompt neutrons in a VVER, the presence of even longer-lived prompt neutrons in CANDU, and, finally, the presence of the longest-lived neutrons in a lead-208 reflector in a fast reactor.

Conclusion

It is shown that due to the long return of neutrons from a physically thick reflector made of lead-208 to the core of a fast reactor, its kinetics is drastically slowed down. This leads to a significant power growth slowing-down during the insertion of positive reactivity in comparison with the same reactor, but with a reflector made of natural lead, and even in comparison with thermal reactors of the VVER and CANDU type, which are traditionally charac-terized by slower kinetics as compared to fast reactors. As a result, the generation of energy not removed from the fuel to the coolant is significantly slowed down. All this means that such a reactor is safer in terms of nuclear accidents.

Richard Feynman called fast assembly a 'slumbering dragon', meaning the catastrophically rapid development of a fission chain reaction even when the value of inserted reactivity approaches the effective delayed neutron fraction. The use of a physically thick lead-208 reflector makes it possible to divert this 'sword of Damocles' from fast reactors not only when the reactivity approaches but even exceeds the value of the effective delayed neutron fraction.

Acknowledgements

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