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Research Article

Safety features of fast reactor with heavy atomic weight weakly neutron absorbing reflector*

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Abstract

The purpose of the present study is the justification of the possibility of improving fast reactor safety by surrounding reactor cores with reflectors made of material with special neutron physics properties.

Such properties of ^{208}Pb lead isotope as heavy atomic weight, small neutron absorption cross section, and high inelastic scattering threshold result in certain peculiarities in neutron kinetics of the fast reactor equipped with ^{208}Pb reflector, which can significantly enhance reactor safety.

The reflector will also make possible generation of additional delayed neutrons characterized by the "dead" time. This will improve the resistibility of the fission chain reaction to stepwise reactivity excursions and exclude prompt super-criticality. Let us note that generation of additional delayed neutrons can be shaped by reactor designers.

The relevance of the study amounts to the fact that generation of additional delayed neutrons in the reflector will make it possible mitigating the consequences of a reactivity accident even if the introduced reactivity exceeds the effective fraction of delayed neutrons. At the same time, the role of the fraction of delayed neutrons as the maximum permissible reactivity for reactor safety is depreciated.

Scientific originality of the study pertains to the fact that the problem of yield of additional neutrons with properties close to normal delayed neutrons, has not been posed before. The authors suggest a new method for enhancing safety of fast reactors by increasing the fraction of delayed neutrons due to the time delay of prompt neutrons during their transfer in the reflector.

In order to benefit from the expected advantages, the following combination is acceptable: lead enriched by ^{208}Pb is used as a neutron reflector while natural lead or other material (sodium, etc.) is used as a coolant in the reactor core.

Keywords

Nuclear safety, reactivity accident, delayed neutrons, fast reactor, radiogenic lead

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Introduction

It is known (Bell and Glasstone 1970) that kinetics of nuclear reactors is comparatively slow with introduction of positive reactivity smaller than the effective fraction of delayed neutrons since the kinetics is determined by the average lifetime of neutrons (0.3–80 s). In contrast, in the case of introduction of reactivity exceeding the fraction of delayed neutrons the kinetics becomes fast, since it is determined by significantly shorter average lifetime of prompt neutrons: ~ 0.1–1 μs for fast reactors and ~ 0.1–1 ms for thermal reactors.

It is specifically the use of light moderators in terms of atomic weight such as, for instance, water and graphite, which allows increasing the average neutron lifetime in thermal reactor by three–four orders of magnitude as compared with fast reactors and correspondingly slowing down the development of fission chain reaction on prompt neutrons.

The purpose of the present study is to slow down the kinetics of fast reactor and thus to enhance its safety. This can be achieved by slowing down neutrons and protracting neutron diffusion in terms of time. Simultaneously it is necessary to retain hard neutron spectrum in the fast reactor core and, thus, application of light moderators is not permissible. This makes the task contradictory and complicated. The solution is possible if the fraction of moderated neutrons will be low while their lifetime will be long. The first condition will allow retaining hard neutron spectrum while the second condition allows increasing the average neutron lifetime. Such possibility is opened by application of heavy moderators in terms of their atomic weight with low neutron absorption.

Application of reflector consisting of natural lead is possible in fast reactor. Within hard energy region natural lead is characterized with intensive inelastic neutron scattering, while in the soft energy region neutron absorption is significant and, therefore, neutrons are actively moderated and after that, being already moderated, they cannot return in the reactor core because they are absorbed by lead.

It is known that ^{208}Pb lead isotope has high inelastic scattering threshold and, therefore, weakly moderates neutrons within hard energy region while its absorption cross-section within soft energy region is small (Shmelev et al. 1991, 1992, 1992a, 1992b, 1993). When radiogenic lead with predominant concentration of ^{208}Pb or lead enriched with ^{208}Pb isotope is used for the purpose instead of natural lead then application of physically thick reflector representing neutron moderator with high atomic weight as well as reflector with improved reflecting properties becomes possible. This allows returning part of leakage neutrons in the reactor core with time delay, i.e. supplying in the fast reactor core supplementary delayed neutrons which can be called the reflector delayed neutrons (or the reflected delayed neutrons) to differentiate them from normal delayed neutrons resulting from the decay of neutron-emitting fission fragment nuclei. This will favorably influence the fast reactor kinetics and will enhance the reactor safety (Shmelev et al. 2011, 2013).

It has to be noted that thorough studies of moderation and transfer of neutron pulses in physically thick media containing moderator with large atomic weight were implemented during the 40–50-ies of the previous century (Isakov et al. 1984, Bekurtz and Wirtz 1968).

Neutronics properties of lead

Lead is characterized by comparatively high atomic weight and, therefore, average logarithmic loss of energy by neutrons in inelastic scattering on lead is small (about 1% (Physical Values 1991)). It is also known that high energy neutrons (more than 1 MeV) after elastic scattering on heavy nuclei predominantly retain their original travel direction (Soppera et al. 2014). The above two factors result in the possibility of deep penetration of high energy leakage neutrons from the reactor core in the lead moderator. Due to high first nuclear excitation level ^{208}Pb isotope possesses high neutron inelastic scattering threshold (2.6 MeV (Soppera et al. 2014)) as compared with other lead isotopes (0.6–0.9 MeV (Soppera et al. 2014)), i.e. ^{208}Pb less intensively moderates neutrons within mega-electron-volt energy region and, therefore, neutrons penetrate deeper in the reflector.

^{208}Pb nucleus is doubly magic, i.e. its neutron and proton shells are closed. Evidently this is the reason why ^{208}Pb isotope is characterized by extremely low neutron absorption cross-section as compared with other lead isotopes (Physical Values 1991) with, noticeably, resonances found only at high energies. This leads to the result that, firstly, in the reflector made of ^{208}Pb the probability for neutrons to slow down to thermal energies without absorption is high (almost 100% (Shmelev et al. 2011, 2013)) as compared with natural lead (only about 30% (Shmelev et al. 2011, 2013)). Secondly, mean square displacement of thermal neutrons during their diffusion in ^{208}Pb (about 8 m (Shmelev et al. 2011, 2013)) is significantly higher than in natural lead (about 0.3 m (Physical Values 1991)). Let us note that mean square displacement for neutrons moderated in lead from fission spectrum to thermal energies weakly depends on its isotopic composition and amounts to about 2 m (Beckman 2010). This means that after moderation as the result of diffusion thermal neutrons have the possibility to return in the reactor core from the depth of ^{208}Pb reflector, while practically all neutrons will be absorbed by the reflector made of natural lead. Thirdly, average lifetime of thermal neutrons in natural lead amounts to only about 1 ms (Beckman 2010) while in ^{208}Pb its value is enormous–about 0.6 s (Shmelev et al. 2011, 2013). Time of neutron slowing down from fission spectrum to thermal energies is small and amounts to only several microseconds even in the heaviest media in terms of atomic weight (Shmelev et al. 2011, 2013, Physical Values 1991, Beckman 2010, Kuzmin 2007). As the result, reflector based on ^{208}Pb isotope (in contrast to natural lead) allows returning back in the reactor core some part of leakage neutrons which will contribute in the fission chain reaction with significant time delay. This will slow down the reactor kinetics and will favorably affect nuclear safety of the fast reactor. For other liquid metal reflectors such as sodium and bismuth (Kuzmin 2007, Marchenko and Sergeev 1969, Kabanova and Kuzmin 2014) the above examined characteristics are close to natural lead being significantly inferior to those for ^{208}Pb.

The above neutronics characteristics of ^{208}Pb predetermine the manifestation of new special features of fission chain reaction in the fast reactor kinetics.

Special features of fission chain reaction important for fast reactor kinetics

Lead-cooled low-power (300 MW) fast reactor with the arrangement and composition of reactor core subzones typical for this reactor type was examined within the framework of spherical geometry. Calculations were performed within the framework of 26-group diffusion approximation using TIME26 computer code (Apse and Shmelev 2008). BNAB-78 nuclear data library and ARAMACO-S1 software complex for preparing nuclear cross-sections were used as the nuclear data support.

Let us examine special features of fission chain reaction in the fast reactor with reactor core surrounded by reflector with high atomic weight and weak neutron absorption.

Supplementary delayed neutrons

Spectrum of moderated neutrons is formed within the depth of the reflector which diffuse to the core serving as supplementary delayed neutrons in the fission chain reaction. The reflector converts leakage prompt neutrons into neutrons which are close in terms of their characteristics to delayed neutrons emitted from fission fragments. This leads to factual increase of the overall fraction of delayed neutrons.

Contribution of neutrons with different lifetimes in the criticality of fast and thermal reactors is shown in Figure 1.

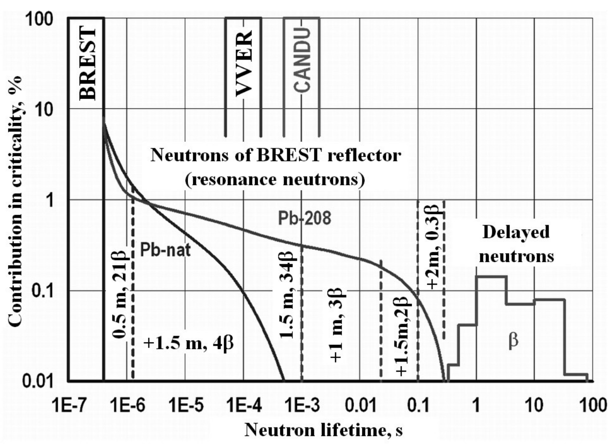

Figure 1. Contribution of neutrons with different lifetimes in the criticality of fast and thermal reactors.

If the core of lead cooled fast reactor is covered with 0.5-m thick reflector made of natural lead then the reflector will be returning in the reactor core leakage neutrons significantly contributing in the reactor reactivity (~ 21×β, where β is the effective fraction of delayed neutrons). However, lifetime of these neutrons is short (~ 1 μs) and is not significantly different from the lifetime of neutrons not leaving the core (~ 0,4 μs). Increase of the reflector thickness by 1.5 m will return in the reactor core neutrons with contribution in reactivity ~ 4×β and lifetime of up to 0.5 ms which corresponds to the lifetime of prompt neutrons in the CANDU-type reactor, i.e. it is still too low. This is explained by significant neutron absorption cross-section for natural lead. As the result, neutrons with long lifetime cannot return in the reactor core from the depth of the reflector and are absorbed by natural lead during their diffusion. This, unfortunately, does not allow slowing down to a significant extent the development of fission chain reaction.

The same can be stated with respect to reflector made of ^{208}Pb with up to ~ 1.5-m thickness which, although it returns neutrons in the reactor core with significant total contribution (~ 34×β), maximum lifetime of these neutrons does not exceed 1 ms, i.e. it is equal to that in CANDU reactors. However, addition of one more meter to the reflector thickness returns in the reactor core neutrons with lifetime of up to 0.03 s and contribution in the reactivity ~ 3×β. Lifetime of these neutrons is already significantly longer than the average neutron lifetime in CANDU reactors (~ 1 ms) and is already close to the most short-lived group of delayed neutrons emitted from fission fragments (0.3 c), while contribution of these neutrons in the fission chain reaction is by ~ 70 times higher than for the most short-lived group. Such neutrons are already capable to slow down the development of fission chain reaction. Additional 1.5 m of reflector thickness will return in the reactor core neutrons with lifetime of up to 0.1 s and contribution in reactivity ~2×β. Addition of 2 more meters of the reflector returns neutrons which, in terms of their lifetime, come immediately close to delayed neutrons emitted from fission fragments (0.3 s). Unfortunately, their contribution is already small (~ 0.3×β) and such reflector thicknesses appear not to be realistic.

Thus, neutrons supplied from fast reactor reflector made of lead-208 fill up the spectrum of time delays between prompt neutrons and delayed neutrons emitted from fission fragments in terms of their lifetime within the range from fractions of microseconds to fractions of seconds. Here, contribution in the fission chain reaction of the most long-lived neutrons is comparable with and even exceeds that for delayed neutrons emitted from fission fragments while their lifetime is by several orders of magnitude longer than the average lifetime of neutrons in thermal reactor. This allows slowing down the development of fission chain reaction and, thus enhance fast reactor nuclear safety.

"Dead" time for supplementary delayed neutrons

It is known that delayed neutrons emitted from fission fragments similarly to prompt neutrons not penetrating the reflector start to contribute in the fission chain reaction immediately following the act of fission although the effect produced by them is extended in time. In contrast to those delayed neutrons the reflected delayed neutrons always have the "dead" time during which they cannot in principle contribute in the fission chain reaction. This "dead" time is formed as the sum of time of neutron diffusion from the reactor core to the reflector and back. This feature of reflected neutrons is favorable for the fast reactor safety.

Stability of fission chain reaction against stepwise reactor power excursion

In the fast reactor under study fission chain reaction is characterized by stability against sharp stepwise power excursion. Due to the increased fraction of delayed neutrons even with introduction of reactivity in excess of the fraction of delayed neutrons emitted from fission fragments (but, nevertheless, smaller than the total fraction of delayed neutrons from fission fragments and from the reflector) fission chain reaction will be boosted not by prompt neutrons with extremely short lifetime which never escape the reactor core but, instead, by the reflector delayed neutrons with average lifetime longer by several orders of magnitude. Therefore, power excursion will develop without sharp stepwise increase of power yield and will be slowed down in time.

Evolution of relative rate of power increase is shown in Figure 2 for asymptotic reactor power excursion depending on the introduced reactivity. Lead cooled fast reactor configurations with 0.5-m thick reflector made of natural lead and with 4-m thick reflector made of ^{208}Pb as well as CANDU-type reactor were examined.

It is clear that lead cooled fast reactor with reflector made of natural lead is characterized by stepwise increase of relative rate of reactor power surge (or stepwise decrease of asymptotic reactor surge period) when reactivity close to the fraction of delayed neutrons emitted by fission fragments is introduced. Thus, with reactivity increased from 0.8×β to 1.2×β fission chain reaction boost by approximately three orders of magnitude is observed. At the same time chain reaction in the same fast reactor equipped with ^{208}Pb reflector, as well as in CANDU-type reactor, is accelerated by only several times. Notably, acceleration rate for such fast reactor is even smaller than for CANDU reactor which, along with RBMK-type reactor, is characterized by the slowest development of fission chain reaction because it has the longest average neutron lifetime (~1 ms).

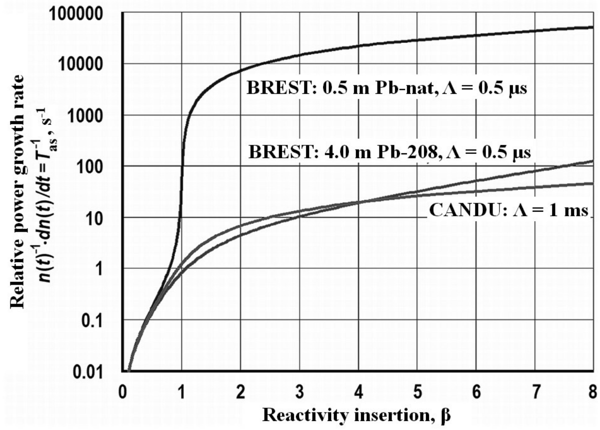

Figure 2. Relative rate of increase of reactor power depending on the introduced reactivity for lead-cooled fast reactors equipped with different reflectors and for CANDU-type reactor.

Generation of supplementary delayed neutrons

Reflector delayed neutrons are generated outside the reactor core and, consequently, this opens the possibility to shape both the neutron lifetime spectrum and the fraction of reflected delayed neutrons using different one-layer and multi-layer reflector configurations. For fuel nuclides lifetimes and fractions of delayed neutrons have practically fixed values and it is not possible to control them.

Increase of Doppler-effect value in the reactor core

Purposeful shaping emission of resonance neutrons returning to the reactor core from the reflector is possible. This will allow increasing the value of Doppler-effect which, in turn, will help enhancing fast reactor safety.

Nonoccurrence of prompt supercriticality

Control rods arranged in the reflector will influence the development of fission chain reaction only using reflector delayed neutrons. Prompt criticality of the reactor core will not be affected in this case. This is associated with the presence of two types of delayed neutrons with essentially different origin–namely, neutrons emitted from fission fragments and neutrons penetrating the core from the reflector. Therefore, worth of control rods arranged in the reflector with be smaller than the total fraction of delayed neutrons by the value of the effective fraction of delayed neutrons emitted from fission fragments. This means that if all control rods will be installed entirely in the reflector, then such reactor will not be subjected to power excursions on prompt neutrons which, naturally, will enhance the reactor safety.

Kinetics with variable characteristics of delayed neutrons

If control rods will be arranged in the reflector, then the reactor will have fission chain reaction kinetics of which is characterized by variable fraction of delayed neutrons and variable neutron lifetime. Molten salt reactor and gas-phase reactor where the functions of fuel and coolant are combined and, therefore, part of fuel is extracted either in liquid or in gaseous form for removing heat from the core to heat exchanger, possess such feature (Blinkin and Novikov 1978). Important difference is associated with the fact that only delayed neutrons emitted from fission fragments are present in these reactors and, therefore, delayed neutron fraction in the rector core is depleted. Alternatively, in the fast reactor under discussion the fraction of delayed neutrons is increased since they include not only neutrons escaping fission fragments but, as well, reflector delayed neutrons.

Potential associated with leakage neutrons

Natural lead is characterized by the combination of inherently mutually contradicting parameters. Large atomic weight leads to slow neutron moderation and, therefore, to deep penetration of neutrons in the reflector. However, significantly high absorption cross-section for moderated neutrons does not allow them returning to the reactor core.

Thus, sizeable field of neutrons not capable to return in the core and to contribute in the fission chain reaction is formed on the periphery of the reflector made of natural lead. Estimations demonstrate that neutron leakage from the outer surface of reflector made of natural lead with thickness equal to 0.5 and 1 m amounts to more than $30\times\beta$ and $20\times\beta$, respectively. Without doubt such significant neutron potential associated with irrevocably leaking neutrons must be utilized. In order to achieve this, fertile nuclides can be arranged, for instance, outside the reflector for breeding fissile material or for transmuting nuclear wastes (minor actinides or fission fragments).

Coupled two-zone system

It was estimated that leakage from the outer surface of reflector made of ^{208}Pb even with thickness of 2 m and 4 m amounts to more than $22\times\beta$ and $15\times\beta$, respectively, i.e. it is significant. Therefore, if breeding blanket is arranged behind such reflector, it will be capable to significantly multiply leakage neutrons part of which can return in the core thus increasing the fraction of delayed neutrons. Thus, a coupled system consisting of fast reactor core and breeding zone with softened neutron spectrum is formed (Kobayashi 1991, Avery 1958, 1958a, Avery et al. 1959). It is specifically leakage neutrons which will ensure coupling of such system. Notably, the core will be subcritical without neutrons penetrating from the annular breeding zone and the rate of development of fission chain reaction in the core will be determined by the prolonged lifetime of neutrons in the annular breeding zone. This will, naturally, enhance safety of the fast reactor under study.

Doppler-effect in the annular breeding zone

If annular breeding zone with low heat conductivity is arranged behind the ^{208}Pb reflector and resonance neutron spectrum is established within this zone, then in the case of neutron burst in the reactor core the annular breeding zone will rapidly warm up an, due to the Doppler-effect, absorption of reflector neutrons will become more intensive while the core will be subcritical without these neutrons. This will result in the slowing down of fission chain reaction in the core. Thus, fast reactor safety will be enhanced.

Exclusion of external fuel cycle

Since leakage in the cavity from the external surface of ^{208}Pb reflector is found to be significant, then it is reasonable to arrange behind the reflector the annular breeding zone with resonance-epithermal neutron spectrum formed inside it. The possibility of direct use of excess neutrons from fast reactor core in the zone with softened neutron spectrum opens within such coupled two-core system. By achieving this the possibility can be realized to use the fuel bred within the zone with softened neutron spectrum essentially bypassing ex-core handling operations performed within external nuclear fuel cycle. Consequently, the functions of thermal and fast reactors will be combined within such coupled system. However, liquid metal technology more complex as compared with liquid water thermal reactors on the basis of VVER or RBMK technology will have to be applied in this case in the zone with softened neutron spectrum. Nevertheless, exclusion of external fuel cycle may prove to be promising. Let us note that similar idea was discussed in (Kobayashi 1991, Avery 1958, 1958a, Avery et al. 1959) where, however, the use of fairly thin reflector made of natural uranium moved in close contact with fast reactor core propped up from the outside with beryllium moderator and high-density depleted uranium was suggested.

^{208}Pb resources

Customary lead with constant isotopic composition (1.4% ^{204}Pb, 24.1% ^{206}Pb, 22.1% ^{207}Pb and 52.4% ^{208}Pb) as well as radiogenic lead characterized with variable isotopic composition since ^{208}Pb, ^{206}Pb and ^{207}Pb isotopes are the final products of decay chains started with ^{232}Th, ^{238}U and ^{235}U, respectively, are found in geological formations. Consequently, radiogenic lead with high concentration of ^{208}Pb in it (more than 90%) can be extracted from the fields of thorium and thorium-uranium ores (Godoy et al. 2007, Catalogue of Isotope Dates 1978) without isotopic separation. However, as it was demonstrated by calculations, in order to make benefit from the advantages of ^{208}Pb concentrations in radiogenic lead of ^{204}Pb and ^{207}Pb isotopes characterized with significant neutron absorption cross-section must be less than 1%. Isotope Interregional Association associated with Rosatom State Atomic Energy Corporation offers services on lead enrichment with ^{208}Pb isotope up to 99.8% (JSC "All-Regional Association "ISOTOPE").

Conclusion

It was demonstrated that neutronics properties of ^{208}Pb result in a number of particular features of kinetics of fast reactor equipped with such reflector which can to a significant extent contribute in enhancing nuclear safety of the reactor.

Combination where the reflector consists of ^{208}Pb and coolant is made of radiogenic lead is permissible for implementing the safety advantages addressed in the present study.

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