The influence of neutron reflector with special properties on fast reactor kinetics

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Abstract. The paper substantiates the possibility of increasing the safety of fast reactors by surrounding the reactor core with a neutron reflector with special properties. The particular case of using lead isotope as a neutron reflector has been considered in the lead-cooled fast reactor in an exemplary manner. An asymptotic point kinetics model, which takes into account neutrons returning from the reflector to the reactor core and participating in the development of fission chain reaction, was proposed for assessment of the emerging effects. The in-hour equation for fast reactors, surrounded by a neutron reflector with special properties, has been developed. It was revealed that the neutron lifetime can be substantially increased. Therefore, the contribution of the neutron reflector would mitigate the consequences of accidents when inserted reactivity exceeds the effective fraction of delayed neutron. In addition, the maximum rates of power increase have been calculated for different cases of reactivity insertion. The obtained results have considerable practical value for scientific and advanced studies of reactor accidents.

1. Introduction

The neutron lifetime is an important parameter of the reactor kinetics. When the inserted reactivity is more than the effective fraction of delayed neutron, the reactor kinetics becomes very rapid process. The fast reactor kinetics can be slowed down by increasing the neutron lifetime.

Using a reflector with special physical properties we can therefore expect that prompt neutrons will be converted into neutrons that are close to delayed neutrons in terms of time delay. This can lead to an increase in the total fraction of delayed neutron, and, subsequently, to the longer reactor period which mitigates the effects of prompt super-criticality.

The article [1] considers the possibility of using lead isotope $^{208}\text{Pb}$ as a neutron reflector with specific properties in the lead-cooled fast reactor. Such specific properties of $^{208}\text{Pb}$ as large atomic weight, weak neutron absorption allow neutrons from the reactor core to penetrate deeply into $^{208}\text{Pb}$-reflector, slow down there and have a noticeable probability to return to the reactor core and affect the chain fission reaction. An asymptotic point kinetics model has been chosen to assess the emerging effects. The model takes into account the effects produced by neutrons returning from $^{208}\text{Pb}$-reflector to the reactor core.
2. The point kinetics model taking into account reflector neutrons

An asymptotic point kinetics model has been developed taking into account neutrons returning from a reflector with specific physical properties to the reactor core and affecting the chain fission reaction for assessment of the peculiarities arising in fast reactors. The one-point kinetics model with one group of delayed neutrons emitters has been chosen for evaluation. The system of equations describing the asymptotic point kinetics model of the fast reactor can be written in the following form:

\[
\frac{dn(t)}{dt} = \frac{\rho_{\text{prompt}}}{\Lambda} n(t) + \lambda C(t) + \frac{\beta_R}{\Lambda} n(t - \tau);
\]

\[
\frac{dc(t)}{dt} = \frac{\beta}{\Lambda} n(t) - \lambda C(t),
\]

where \(\beta_R\) – fraction of neutrons returning from reflector to the reactor core, \(\tau\) – “dead-time” which represents the sum of times when neutrons leave the reactor core entering reflector and then diffuse back into the reactor core. During the “dead-time” these neutrons cannot affect the chain fission reaction. The asymptotic point kinetics model properly takes into account the neutrons coming back from reflector after the “dead-time”. In the paper the neutron “dead-time” is correctly taken into account in the terms of delay rather than in the terms of decay as it was done in paper [1].

The paper considers the model with neutron lifetime much shorter than the lifetime of delayed neutron emitters to simplify the analysis of the equation system. This approach allows neglecting the summand related to the contribution of delayed neutron emitters. Thus, the equation describing the neutron density might be written in the following form:

\[
\frac{dn(t)}{dt} = \frac{\rho_{\text{pr}} + \rho_R}{\Lambda} \frac{n(t-\tau)}{n(t)} n(t).
\]

While reactor mode is operable, \(\frac{n(t-\tau)}{n(t)} = 1\). When the positive reactivity is inserted, the neutron density \(\frac{dn(t)}{dt}\) would be slowed down, because \(\frac{n(t-\tau)}{n(t)} < 1\). If the chain reaction fades away or comes to a halt, the relative neutron density \(\frac{n(t-\tau)}{n(t)}\) would increase, and the value \(\frac{dn(t)}{dt}\) would grow. Therefore, the reactor can be operated to maintain its critical condition for long periods of time.

The reactivity and fraction of neutrons returning from the reflector to the reactor core have the following values at the initial moment:

\[
\rho_{\text{pr}} = \rho_0^{\text{pr}} + \delta \rho_{\text{pr}} = 0; \tag{4}
\]

\[
\beta_R = \beta_0 + \delta \beta_R = 0. \tag{5}
\]

Taking into account these expressions, the equation (3) may be re-written in the following form:

\[
\frac{dn(t)}{dt} = \frac{\rho_0^{\text{pr}} + \delta \rho_{\text{pr}}}{\Lambda} n(t) + \frac{\beta_0 + \delta \beta_R}{\Lambda} n(t - \tau). \tag{6}
\]

Using Taylor’s expansion to the function decomposition, we can convert the second summand. The first two terms were selected for further assessment because of the features of an asymptotic point kinetics model.
\[ n(t - \tau) = \frac{n(t - \tau)}{n(t)} n(t) = \frac{n(t) - \frac{\text{dn}}{n(t) \text{dt}}} {1 - \frac{1}{n(t)} \frac{\text{dn}}{n(t) \text{dt}}} n(t). \] (7)

The equation (6) will have the following form after the modification:
\[ \frac{\text{dn}(t)}{\text{dt}} \cong \frac{\rho_0^{pr} + \delta \rho^{pr} + \beta_0^R + \delta \beta^R - (\beta_0^R + \delta \beta^R) \tau}{\Lambda} \frac{\text{dn}}{n(t) \text{dt}} n(t). \] (8)

When \( t \geq 0, \rho_0^{pr} + \beta_0^R = 0 \), therefore:
\[ \frac{\text{dn}(t)}{\text{dt}} \cong \frac{\delta \rho^{pr} + \delta \beta^R - (\beta_0^R + \delta \beta^R) \tau}{\Lambda} \frac{\text{dn}}{n(t) \text{dt}} n(t). \] (9)

Moving forward, the left and right part of the equation (9) can be multiplied by the lifetime of prompt neutrons \( \Lambda \) and divided by the neutron density \( n(t) \).
\[ \Lambda \frac{\text{dn}(t)}{n(t) \text{dt}} \cong \frac{\delta \rho^{pr} + \delta \beta^R - (\beta_0^R + \delta \beta^R) \tau}{\Lambda} \frac{\text{dn}}{n(t) \text{dt}} \] (10)

Move the derivative from the right part to the left.
\[ [\Lambda + (\beta_0^R + \delta \beta^R) \tau] \frac{\text{dn}(t)}{n(t) \text{dt}} \cong \delta \rho^{pr} + \delta \beta^R. \] (11)

Dividing both parts of (11) by the neutron lifetime, the equation describing the neutron density with accounting for the neutrons coming back from the neutron reflector might be written in the following form:
\[ \frac{\text{dn}(t)}{\text{dt}} \cong \frac{\delta \rho^{pr} + \delta \beta^R}{[\Lambda + (\beta_0^R + \delta \beta^R) \tau]} n(t). \] (12)

According to the equation (12), the neutron density can be reduced due to the longer neutron lifetime formed by the prompt neutron lifetime and “dead-time” of the neutrons from reflector layers with specific physical properties. This can lead to the longer reactor period which mitigates the effects of prompt super-criticality when the positive reactivity is inserted. Thus, the use of a reflector can improve significantly the safety of the fast reactor.

If the chain fission reaction develops with asymptotic period \( T \) \( (n(t) \sim \text{exp}(t/T)) \), then the function \( \frac{1}{n(t)} \frac{\text{dn}(t)}{\text{dt}} \cong \frac{1}{T} \) would characterize the relative energy release rate in the chain fission reaction. Therefore, the expression (9) can be re-written as follows:
\[ \frac{\text{dn}(t)}{\text{dt}} \cong \frac{\delta \rho^{pr} + \delta \beta^R - (\beta_0^R + \delta \beta^R) \tau}{\Lambda} \frac{\text{dn}}{n(t) \text{dt}} n(t). \] (13)

The negative reactivity feedback effect related to the neutron reflector \( \left\{ - (\beta_0^R + \delta \beta^R) \tau \frac{\text{dn}}{n(t) \text{dt}} \right\} \) is proportional to the relative energy release rate in the chain fission reaction \( \frac{1}{n(t)} \frac{\text{dn}(t)}{\text{dt}} \). The chain fission reaction has a steady state at the initial moment. When reactivity is inserted, it begins to dissipate the chain fission reaction, and the term associated with the contribution of reflector neutrons has not been included yet. Afterwards, an additional term proportional to the function \( \frac{1}{n(t)} \frac{\text{dn}(t)}{\text{dt}} \) appears with the
negative sign that results in the decreasing of the inserted reactivity while $\beta_R \neq 0$, $\tau \neq 0$, and, as a result, the neutron density decreases.

The in-hour equation may be written in the following form for the model taking into account the neutrons coming back from the neutron reflector:

$$\delta \rho_{pr} = \Lambda \frac{1}{n(t)} \frac{dn(t)}{dt} - \delta \beta_R + (\beta_0^R + \delta \beta_R) \tau \frac{1}{n(t)} \frac{dn(t)}{dt}.$$  \hspace{1cm} (14)

Combining the components related to the derivative, the equation (14) can be re-written in the form:

$$\delta \rho_{pr} = [\Lambda + (\beta_0^R + \delta \beta_R) \tau] \frac{1}{n(t)} \frac{dn(t)}{dt} - \delta \beta_R.$$  \hspace{1cm} (15)

If the chain fission reaction develops with asymptotic period $T$ ($n(t) \sim \exp (t/T)$), the equation (15) could be converted to the form:

$$\delta \rho_{pr} = [\Lambda + (\beta_0^R + \delta \beta_R) \tau] \frac{1}{n(t)} \frac{dn(t)}{dt} - \delta \beta_R - \lambda C(t) \frac{\Lambda}{n(t)}.$$  \hspace{1cm} (16)

The equation (16) is the in-hour equation for the model where the reactor core is surrounded by a neutron reflector with specific physical properties, and neutrons returning from the reflector to the reactor core affect the chain fission reaction.

3. Neutron flash

When the positive reactivity is inserted to the system, a rapid increase in the prompt neutron population can be observed. Two versions of reactivity insertion have been considered in this section: insertion to the reactor core and to the neutron reflector. The reactivity changes abruptly up to $\rho$, exceeding the reactivity that corresponds to the reactor criticality.

The neutron density for the model without neutron reflector can be described by the following equation:

$$\frac{dn}{dt} = \frac{\delta \rho_{pr} - \Lambda \frac{1}{n(t)} \frac{dc}{dt}}{\Lambda} n(t).$$  \hspace{1cm} (17)

If the power level changes quickly then it is possible to neglect the contribution of delayed neutron emitters, because $C = \text{const}$.

The neutron density can be written in the following form: $dn(t)/dt = \alpha_0 n(t)$, where $\alpha_0$ – initial rate of power increase. Respectively, the maximum rate of power increase might be written in the next way:

$$\frac{1}{n(t)} \frac{dn}{dt} = \frac{\delta \rho_{pr}}{\Lambda}.$$  \hspace{1cm} (18)

When the reactivity is inserted to the neutron reflector, the expression (17) describing the neutron density would be re-written as follows:

$$\frac{dn(t)}{dt} \cong \frac{\delta \rho_{pr} + \delta \beta R}{[\Lambda + (\beta_0^R + \delta \beta_R) \tau]} n(t).$$  \hspace{1cm} (19)

The maximum rate of power increase for the case of the insertion of reactivity to the neutron reflector is estimated by an expression
\[
\frac{1}{n(t)} \frac{dn(t)}{dt} \approx \frac{\delta \beta^R}{[\Lambda + (\beta_0^R + \delta \beta^R)\tau]}.
\] (20)

The equation (20) is an approximation of the maximum rate of power increase taking into account neutrons coming back from a reflector to the reactor core. This result is connected with using two first terms of Taylor’s decomposition \( n(t-\tau) \).

If \( \delta \rho^{pr} = \delta \beta^R \) during a neutron flash, so \( \propto \frac{\alpha_{bare}}{\alpha_{ref}} = \frac{\Lambda + (\beta_0^R + \delta \beta^R)\tau}{\Lambda} = 1 + \frac{(\beta_0^R + \delta \beta^R)\tau}{\Lambda} \). (21)

The equation (20) represents the ratio of the maximum rates of power increase during a neutron flash when the inserted reactivity exceeds the effective fraction of delayed neutron. The obtained results have considerable practical value for scientific and advanced studies of reactor accidents because of the opportunity to mitigate the effects of the uncontrolled nuclear chain fission reaction.

4. Conclusion
In the paper, an asymptotic point kinetics model which takes into account neutrons returning from the reflector to the reactor was proposed. According to this, the neutron lifetime formed by the prompt neutron lifetime and the “dead-time” of the neutrons from reflector with specific properties can be substantially increased. The longer neutron lifetime can reduce the neutron density when the positive reactivity is inserted. Thus, the additional contribution of the reflector neutrons can slow down the kinetics of the chain fission reaction.

Similar effects were discovered with using lead isotope \( ^{208}\text{Pb} \) as a physically thick neutron reflector in a lead-cooled fast reactor. Such specific properties of \( ^{208}\text{Pb} \) as large atomic weight, weak neutron absorption allow neutrons from the reactor core to penetrate deeply into \( ^{208}\text{Pb} \)-reflector, slow down there and have a noticeable probability to return to the reactor core and affect the chain fission reaction. The neutrons returning from deep layers of \( ^{208}\text{Pb} \)-reflector are close to the delayed neutrons in the terms of time delay. Moreover, the number of neutrons coming back from \( ^{208}\text{Pb} \)-reflector considerably exceeds the number of delayed neutrons. The use of lead isotope \( ^{208}\text{Pb} \) not only as a coolant but also as a neutron reflector in fast reactor leads to the number of kinetics features. The peculiarity of the neutrons coming back from the \( ^{208}\text{Pb} \)-reflector is a favorable factor for the reactor safety.

To conclude, it has been established that the use of reflector with specific physical properties can significantly increase the safety of the fast reactor.

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