Stochastic theory of zero-power nuclear reactors. Part 2. Probability of the branching process degeneration and issues of estimating the probability of a nuclear accident

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Abstract

A formula has been derived to estimate the degeneration probability in which the conditional probability that the fission process will not stop by the time \( t \) is determined by using a system of nonlinear differential equations presented in the paper. It follows from the formula that whatever the breeding ratio, a branching process with a probability of unity will never arise in a nuclear reactor without an external excitation.

A general relationship has been found for an asymptotic value of the probability that the fission process will stop in the nuclear reactor. It has been shown that Hansen’s model is a quadratic approximation of the general model and always overestimates this probability.

The paper presents a theoretical analysis showing that Hansen’s model underestimates the probability of a nuclear accident as compared to the estimates obtained by using the general model presented in the paper.

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Probability for degeneration of branching process

Herein, the probability for degeneration of the branching process is understood as the probability that, by the time \( t \), no particles of the \( T_1 \) and \( T_2 \) types (prompt neutrons and precursors of delayed neutrons) will remain in the reactor, with the number of the \( T_0 \)-type particles (source neutrons) being random, if there was only one particle of the \( T_0 \) type in the reactor at the initial time \( t = 0 \) (all symbols used herein are the same as in part 1 of [1]). Such understanding of the degeneration probability somewhat differs from that being in common usage [2] and stems from the physical peculiarities of the branching process under investigation (we shall note that it is commonly considered in the theory of branching processes that the generation and death process tends to degenerate if particles of all types disappear).

The thing is that particles of the \( T_0 \) type are neutrons from an external source which are not generated in the neutron breeding process, that is, they do not appear from fission chains. Regardless of whether fission chains, i.e. particles of the \( T_1 \) and \( T_2 \) types, are present or not, the \( T_0 \)-type particles are always present in the reactor in accordance with the distribution of their number depending on the external source power. If the fission chains (and, therefore, the \( T_1 \) and \( T_2 \) particles) disappear by the time \( t \), regardless of if the \( T_0 \)-type particles are present or not, it may be considered that the neutron generation and death branching process in the reactor, which started at the time \( t = 0 \) of the \( T_0 \) particle, had degenerated (stopped) by the time \( t \).

Let the probability of this event be \( P^{(0)}_0(t) \). It is clear that

\[
P^{(0)}_0(t) = \sum_{\alpha_0} P^{(0)}_{\alpha_0}(0,0)(t),
\]

where \( P^{(0)}_{\alpha_0}(0,0)(t) \) is defined in [1]. The probabilities \( P^{(0)}_{\alpha_0,0,0}(t) \) are defined from the generating function \( P^{(0)}(t,s) \).
using formulas [2]

\[
P^{(0)}_{0,0,0}(t) = \prod_{s_0=0}^{(0)}(t, s_0, 0, 0) = 0,
\]

\[
P^{(0)}_{0,0,0}(t) = \frac{\partial \prod^{(0)}_{s_0=0}(t, s_0, 0, 0)}{\partial s_0} = \frac{1}{s_0} \prod^{(0)}_{s_0=0}(t, s_0, 0, 0),
\]

\[
P^{(0)}_{\alpha_0,0,0}(t) = \frac{\partial \prod^{(0)}_{s_0=0}(t, s_0, 0, 0)}{\partial s_0} \bigg|_{s_0=0} = 0 \quad (\alpha_0 > 1),
\]

so

\[
P^{(0)}_{0,0,0}(t) = \frac{\prod^{(0)}_{s_0=0}(t, s_0, 0, 0)}{s_0} \bigg|_{s_0=0}.
\]

It can be seen from system of equations (5') in [1] that the first equation can be solved regardless of how the two others are solved. It has the form

\[
\prod^{(0)}_{s_0=0}(t, s_0) = s_0 \exp \left( -S \int_0^t \left[ 1 - \prod^{(1)}(\tau, s_1, s_2) \right] d\tau \right).
\]

Here, the argument \( S_0 \) is omitted in record \( \Pi^{(1)} \) for brevity, since \( \Pi^{(1)} \) and \( \Pi^{(2)} \) do not depend on \( S_0 \).

Therefore,

\[
P^{(0)}_{0,0,0}(t) = \exp \left( -S \int_0^t \left[ 1 - \prod^{(1)}(\tau, 0, 0) \right] d\tau \right).
\]

The function \( Q^{(1)}_{\Pi}(t) = \prod^{(1)}(t, 0, 0) \) is the probability of the branching process degeneration by the time \( t \), if it started at the time \( t = 0 \) from one \( T_1 \)-type particle. Accordingly, \( Q^{(1)}_{\Pi}(t) = 1 - 1_{QB}^{(1)}(t) \) is the probability of the process continuation after the time \( t \) in the same condition.

Physically, the probabilities \( Q^{(1)}_{\Pi}(t) \) and \( Q^{(1)}_{\Pi}(t) \) are transparent enough. We shall create an “ideal” reactor fully isolated from external neutron sources (natural background, spontaneous fissions and so on). If a single neutron is somehow let into the reactor at the time \( t = 0 \), the branching process starts because there is already one \( T_1 \)-type particle in the reactor. The probabilities \( Q^{(1)}_{\Pi}(t) \) and \( Q^{(1)}_{\Pi}(t) \) are the probabilities that the branching process will come to an end or, accordingly, go on at the time \( t > 0 \) in such “ideal” reactor.

One more initiation of the branching process in an “ideal” reactor may be assumed: one precursor of delayed neutrons (a \( T_2 \)-type particle) is somehow let in the reactor at the time \( t = 0 \). Then it is possible to consider the probabilities \( Q^{(1)}_{\Pi}(t) \), \( Q^{(1)}_{\Pi}(t) = 1 - Q^{(1)}_{\Pi}(t) \) of the branching process degeneration and continuation, respectively.

Thus, formula (2) can be rewritten in the form

\[
P^{(0)}_{0,0,0}(t) = \exp[-S\gamma(t)],
\]

where

\[
\gamma(t) = \int_0^t Q^{(1)}_{\Pi}(\tau) d\tau.
\]

The probability \( Q^{(1)}_{\Pi}(t) \) is found in accordance with system of equations (5') in [1] from the system of nonlinear differential equations

\[
\frac{dQ^{(1)}_{\Pi}}{dt} = \frac{1}{L} \left\{ \frac{k}{\nu} \left( 1 - \sum_{s_0=0}^N r(s) \left[ 1 - (1 - \beta)Q^{(1)}_{\Pi} - \beta Q^{(2)}_{\Pi} \right] s \right) - Q^{(1)}_{\Pi} \right\},
\]

(4)

with the initial conditions

\[
Q^{(1)}_{\Pi}(0) = Q^{(2)}_{\Pi}(0) = 1.
\]

According to formula (3), when \( S = 0 \), that is, when there is no external neutron source in the reactor, \( P^{(0)}_{0}(t) = 1 \) for any \( t \geq 0 \). This means (which is fairly clear) that, without being initiated externally, the branching process will never emerge with a probability of unity in the reactor with any breeding factor.

As follows from [2], it can be shown that system of equations (4) remains valid in the event of a heterogeneous branching process, that is, when \( k \) is the function of the time \( t \).

**Probability of a nuclear accident**

Hereinafter, nuclear accident is understood as an uncontrolled nuclear reactor power excursion due to prompt neutrons. Such nuclear accident takes place if at least one self-sustaining (time-infinite) fission chain occurs when the prompt breeding factor is equal to or greater than unity. Then the neutron population in the reactor grows unlimitedly in a very short time (\( -L \)) [3].

In terms of the nuclear accident probability evaluation, all fission chains initiated by source neutrons can be divided into two complementary classes: a class of non-self-sustaining fission (time-finite) chains and a class of self-sustaining chains.

The branching process degeneration probability \( P^{(0)}_{0}(t) \), defined by formula (3), is also the probability that all fission chains in the reactor in the time interval \([0, t]\) will turn out to be non-self-sustaining, or the probability that the time to the first self-sustaining fission chain (FSFC) will exceed \( t \), so

\[
\lim_{t \to \infty} P^{(0)}_{0}(t) = P^{(0)}_{0}(\infty)
\]

there is a probability that no self-sustaining fission chains will occur in a finite time.

If \( P^{(0)}_{0}(\infty) = 0 \), one may talk about the distribution of the time to the FSFC. It is set by the distribution function \( F(t) = P(\tau \leq t) = 1 - P^{(0)}_{0}(t) \). If \( P^{(0)}_{0}(\infty) \neq 0 \), one should talk about the conventional distribution of the given time, provided the FSFC occurred in a finite time. This conventional distribution is set by the relation

\[
\left[ 1 - P^{(0)}_{0}(\tau) \right] / \left[ 1 - P^{(0)}_{0}(\infty) \right].
\]
Therefore, for the density of the distribution of the time to the FSFC, the formula

\[
f(t) = \begin{cases} 
SQ^{(1)}_I(t) \exp(-SY(t)), & P_0^{(0)}(\infty) = 0; \\
\frac{SQ^{(1)}_I(t)}{1 - P_0^{(0)}(\infty)} \exp(-SY(t)), & P_0^{(0)}(\infty) \neq 0. 
\end{cases}
\]  \tag{6}

is valid.

According to formulae (3) and (6), the time behavior of the functions \(P_0^{(0)}(t)\) and \(f(t)\), and, consequently, the nature of the distribution of the time to the FSFC (including in an asymptotic case when \(t \to \infty\) is fully defined by the function \(\gamma(t)\). This function depends on the probabilities \(Q^{(1)}_I(0)\) and \(Q^{(2)}_I(0)\) of the branching process continuation in an “ideal” reactor which are the solutions to system of equations (4) with initial conditions (5).

A study into the asymptotic behavior of the functions \(Q^{(1)}_I(t)\) and \(Q^{(2)}_I(t)\) with \(t \to \infty\) gives a notion of some important physical peculiarities of the neutron generation and death branching process in a nuclear reactor. According to the theory of branching processes (see [2]), the probabilities

\[
q^{(1)}_B = 1 - q^{(1)}_I = \lim_{t \to \infty} Q^{(1)}_B(t)
\]

and

\[
q^{(2)}_B = 1 - q^{(2)}_I = \lim_{t \to \infty} Q^{(2)}_B(t)
\]

are the components of the vector \(I\), which is the root of the system of equations

\[
\rho^{(1)}(\Pi^{(1)}, \Pi^{(2)}) = 0, \\
\rho^{(2)}(\Pi^{(1)}, \Pi^{(2)}) = 0,
\]

where \(\rho^{(i)}(s)\) are the generating functions of the probability densities for the transition of the branching process under consideration introduced in part 1 hereof.

Therefore, \(q^{(1)}_B\) and \(q^{(2)}_B\), accordingly, the probabilities \(q^{(1)}_I, q^{(2)}_I\) can be found from the system of equations

\[
1 - \pi - q^{(1)}_B + \pi \sum_{v=0}^{N} r(v) \left[ (1 - \beta)q^{(1)}_B + \beta q^{(2)}_B \right]^v = 0, \\
q^{(1)}_B - q^{(2)}_B = 0.
\]

It follows there from that \(q^{(1)}_B = q^{(2)}_B\) and, accordingly, \(q^{(1)}_I = q^{(2)}_I\), that is, the probability of self-sustaining fission chains to occur in a finite time does not depend on due to which particle (of the T1 type or the T2 type) the branching processes started in the “ideal” reactor. The substitution of the solution to the second equation in the first equation leads to a nonlinear equation for \(q^{(1)}_B\)

\[
1 - \pi - q^{(1)}_B + \pi \sum_{v=0}^{N} r(v) [q^{(1)}_I]^v = 0,
\]

\[
(7)
\]

where \(\pi = k/\nu\) is the relation of the breeding factor to the average number of secondary neutrons generated in one fission event.

Therefore, the probability of self-sustained fission chains to occur in a finite time does not depend on the delayed neutron fraction \(\beta\) and the prompt neutron lifetime \(L\), and is defined only by the breeding factor \(k\) and by the distribution \(r(v)\) of the total number of secondary neutrons during fission.

The obvious root of Eq. (7) is \(q^{(1)}_B = 1\). It was proved in [2] that, if Eq. (7) has another, non-unity, root \(0 \leq q^{(1)}_B < 1\), it is the only one and is the sought-after probability \(q^{(1)}_B\). In this case, the branching process is referred to as non degenerating. If there is no root other than the obvious root \(q^{(1)}_B = 1\), the branching process is referred to as degenerating.

An analysis into Eq. (7) shows that the only solution to \(0 \leq q^{(1)}_B < 1\), apart from the obvious one, exists only when \(k > 1\).

Actually, using factorial moments of the distribution \(r(v)\) and taking into account that \(\pi = k/\nu\), Eq. (7) can be given such form as would be more convenient for further analysis

\[
q^{(1)}_I \left\{ 1 + k \sum_{l=1}^{N} \frac{(v-l+1)}{\nu} \frac{(v \rightarrow v-l+1)}{(v-l+1)!} \right\} = 0,
\]

where \(\gamma_l = \frac{r(v)}{v(v-1)\ldots(v-l+1)}\).

Here, \(\gamma_l\) is the factorial moment of the \(l\)th order for the distribution \(r(v)\). The obvious solution \(q^{(1)}_I = 0 (q^{(1)}_B = 1)\) is isolated from Eq. (7), and the only non-obvious solution \(q^{(1)}_I \neq 1\) can be obtained by equating the braced part to zero. After a series of transforms, this equality for \(q^{(1)}_B \neq 1\) assumes the form

\[
\frac{k-1}{k} = \frac{1}{\nu [1 - q^{(1)}_B]} \sum_{v=0}^{N} r(v) \left[ q^{(1)}_I \right]^v + \nu - 1.
\]

Since \(\nu > 1\), \(0 \leq r(v) < 1\) and, by convention, \(0 \leq q^{(1)}_B \leq 1\), then the existence of \(q^{(1)}_I \neq 1\) requires the right-hand side of the obtained equality to be positive. Then it follows from the left-hand side of the equality that the inequality \(k > 1\) should be satisfied for \(k\).

Therefore, in a subcritical or a critical “ideal” reactor \((k \leq 1)\), no self-sustaining fission chains can occur in a finite time with a probability of unity. In a supercritical “ideal” reactor, such chains occur in a finite time with the probability \(q^{(1)}_I = 1 - q^{(1)}_B \neq 0\).

It can be seen from Eq. (7) that, assuming the non-obvious solution \(q^{(1)}_I\) to be small \((q^{(1)}_B \neq 1\) is close to unity), it is enough, to have it estimated, to leave a small number of summands in the total (e.g. up to the power \(q^{(1)}_I \leq 2\) or to estimate the non-obvious solution \(q^{(1)}_I\), e.g. using the formula

\[
q^{(1)}_I \approx \frac{k-1}{k} \frac{v(v-1)}{2\nu}.
\]

The quality of such “quadratic” approximation needs to be estimated.

Fig. 1 presents the results of calculating the dependence \(q^{(1)}_B\) on quantity \(k\) for the reactor with uranium-235 based on Eq. (7) \((\nu = 2.47\) [4]) and the results of the approximate estimation using formula (8).
The quantity $q_B^{(1)} \neq 0$ even with the maximally achievable $k = 2.47$. This stems from that $r(0) \neq 0$, that is, no single neutron is likely to appear during fission with a probability other than zero.

2. With values $k$ being close to unity, but not exceeding it, (actually with $1 + \alpha \beta$ where $0 < \alpha \leq 10$, $\beta \approx 0.0065$), the probability $q_B^{(1)}$ is rather high, e.g. even when $k = 1.1$, that is, it is larger under the super criticality $10\beta$, $q_B^{(1)} \approx 0.9$. Physically, this, for example, means that, out of ten similar “ideal” reactors with a super criticality of $10\beta$, in which the effects from external neutron sources are totally excluded, only one, on the average, will have the FSFC to occur in a finite time after the branching process starts. The other ten will never have such fission chain. Therefore, we have arrived at a non-obvious and maybe even paradoxical conclusion: the fission process started by one neutron (or by a precursor of delayed neutrons) in a reactor without an external neutron source is highly likely to come to an end in a finite time even in highly supercritical conditions ($\approx 10\beta$).

3. “Quadratic” approximation invariably overestimates the probability of the branching process to come to an end in a finite time, and this overestimation is great when values $k$ are large and acceptable under super criticalities of not more than $10\beta$.

So why is it so that the fission chain reaction is nevertheless sustained in real reactors when $k \leq 1$, and even nuclear accident may take place when $k > 1$? The thing is that external neutron sources (natural background, spontaneous fissions, neutron-generating materials, special sources and so on) are always present in any real reactor, so the source intensity is always $S \neq 0$ in a real reactor.

To understand what is happening, we shall look back at the probability $P_0^{(0)}(t)$ for which formula (3) was obtained, and to the distribution $f(t)$ of the time $t$ to the FSFC for which formula (6) was obtained. Let the random event $A_i$ consist in that fission chains arise in the reactor as the result of the $i$th source neutron getting in. In the event when $P_0^{(0)}(\infty) \neq 0$, all fission chains in the time interval $[0, \infty)$ may turn out to be non-self-sustaining with the probability $P_0^{(0)}(\infty)$. Physically, it means that, if the existing fission chains ceased to exist following the appearance of another $i$th source neutron in the reactor, than, after the next $I + 1$th source neutron appears, no fission chains may occur altogether with the probability $P_0^{(0)}(\infty)$. As shown in [5], we deal here with the potential for the chain of events $A_i(i = 1, 2, \ldots, \infty)$ to be broken. In this case, the total number of events $A_i$ is finite and has a geometrical distribution.

When the source intensity $S$ is rather high, the probability $P_0^{(0)}(\infty)$ is very small and the total number of events $A_i$, in the case of the flow break, is finite but great. When $P_0^{(0)}(\infty) = 0$, the event flow $A_i$ does not break with a probability of unity, and the fission process may continue for an infinitely long time. The distribution of the time between the initiations of events $A_i$ is defined in both cases by formula (6). And it needs to be remembered that, in the event of $P_0^{(0)}(\infty) \neq 0$, this distribution is conventional relative to the event flow break. When the neutron source is permanent (even that of a small intensity $S$) and when $P_0^{(0)}(\infty) \neq 0$, following a regular flow of events $A_i$, a new flow of these events starts after time $t$ with the probability $1 - \exp(-St)$ as new source neutrons enter the reactor. And this fission process may continue for an infinitely long time.

According to formula (3) and the definition of the function $\gamma(t)$, the asymptotic behavior of the probability $P_0^{(0)}(t)$ with $t \to \infty$ is defined fully the obtained limiting probabilities $q_B^{(1)}$ and $q_\Pi^{(1)}$ of the branching process degeneration and continuation respectively. Thus, when $k \leq 1$, $q_\Pi^{(1)} = 0$. Following [2], it can be easily shown that $q_\Pi^{(1)}(t) \to 1/t^{1+\delta}$ when $t \to \infty$, while $\delta > 0$ when $k < 1$, and $\delta = 0$ when $k = 1$.

Then the asymptotic behavior of the functions $\gamma(t)$ and $P_0^{(0)}(t)$ when $t \to \infty$ is as follows: when $k < 1$, $\gamma(t) \to C$ and $P_0^{(0)}(\infty) = \exp(-SC) \neq 0$; and when $k = 1$, $\gamma(t) \to \ln t$ and $P_0^{(0)}(\infty) = 0$. In the event when $k > 1$, $q_B^{(1)} \neq 0$, and with $t \to \infty$, $P_0^{(0)}(t) \to \exp(-S\gamma(t)^1)$, that is, $P_0^{(0)}(\infty) = 0$.

Therefore, in a real reactor with a permanently existing external source of neutrons, a chain fission reaction proceeds in general as follows. When $k < 1$, the fission chains are finite with a probability of unity and occur as “wave trains”. The distribution of the time between the appearances of fission chains inside a wave train depends on the source intensity $S$ and on the branching process continuation probability $q_\Pi^{(1)}(t)$. The distribution of the time between the wave trains depends only on the source intensity $S$. When $k \geq 1$, fission chains emerge uniformly in time, and, when $k = 1$, they are finite with a probability of unity.

As in [6], we shall determine the probability of the nuclear accident initiation by the time $t$ as the probability $1 - P_0^{(0)}(t)$ of the FSFC appearance in the time interval $[0, t]$, provided that such conditions of breeding had arisen spontaneously in the reactor by the time $t = 0$ that $k > 1$ when $t \geq 1$. As follows from the aforesaid, this probability is defined by the neutron source intensity $S$ and by the probability $q_\Pi^{(1)}(t)$ of the branching
process continuation after the time \( t \) if the branching process was started by one neutron.

To compute the probability of the nuclear accident initiation, one should solve system of nonlinear differential equations (4) with variable coefficients (if \( k \) depends on \( t \)) and initial conditions (5). This system is rather difficult to solve computationally so its reasonable approximations are required. For instance, it is possible to neglect delayed neutrons (to assume that \( \beta = \lambda = 0 \)), and, accordingly, \( Q_{\Pi}^{(2)}(t) = 0 \). Then system of equations (4) transforms into one nonlinear differential equation for \( Q_{\Pi}^{(1)}(t) \) which can be conveniently written, using the factorial moments \( \gamma_l \) of the distribution \( r(\nu) \), in the form

\[
\frac{dQ_{\Pi}^{(1)}}{dt} = \frac{1}{L} \left\{ k \left( 1 - \sum_{l=1}^{\infty} (-1)^l \frac{\gamma_l}{l!} \left( Q_{\Pi}^{(1)} \right)^l \right) - Q_{\Pi}^{(1)} \right\}.
\]

The initial condition remains the same:

\[
Q_{\Pi}^{(1)}(0) = 1.
\]

Further simplification may be done, say, with high powers neglected in the total of the right-hand side of Eq. (9), if you are sure that \( Q_{\Pi}^{(1)}(t) \) is not very large. By reason of the initial condition, this is possible if it is enough to know the solution \( Q_{\Pi}^{(1)}(t) \) when values \( t \) are large.

**Analysis of Hansen’s model**

Hansen’s model [6] has been used extensively to estimate the probabilities of nuclear accidents at radiochemical production sites [7], as well as to justify physical characteristics of pulsed nuclear reactors [8]. It broadly uses the distribution \( f(t) \) of the time to the FSFC and the moments of this distribution. As can be seen from formula (6), the distribution obtained herein differs greatly from the same distribution obtained by Hansen. Hansen’s model does not take into account in any way the potential for the branching process to stop, so according to Hansen’s model,

\[
f(t) = S \cdot Q_{\Pi}^{(1)}(t) \cdot \exp \{-S\gamma(t)\}.
\]

To estimate the probabilities of a nuclear accident and the moments of the distribution of the time to a nuclear accident, this expression is true when \( k \geq 1 \). It should be however remembered that no total moments of the distribution of the time to the FSFC exist when \( k < 1 \), and one may talk only about the conventional moments of this distribution provided that the FSFC occurs in a finite time. The probability of this event is \( 1 - P_0^{(0)}(\infty) \) and is very small when \( S \) is small.

Let us consider Eq. (9) with initial condition (10). We shall assume that, with values \( t \) being rather large, the values \( Q_{\Pi}^{(1)}(t) \) are so small that only powers \( Q_{\Pi}^{(1)}(t) \), not exceeding 2, can be left in the total of the equation’s right-hand side. Then \( Q_{\Pi}^{(1)}(t) \) can be estimated from the equation

\[
\frac{dQ_{\Pi}^{(1)}}{dt} = \frac{k - 1}{L} Q_{\Pi}^{(1)} - \frac{k}{L} \frac{\nu (\nu - 1)}{2} \frac{Q_{\Pi}^{(1)}}{Q_{\Pi}^{(2)}}
\]

with initial condition (10). It can be seen that this equation and relation (8) for estimating the limiting probability \( q_{\Pi}^{(1)} \) is fully identical to the results obtained based on Hansen’s model.

Therefore, Hansen’s model:

- is the “quadratic” approximation of the branching process general model built herein to estimate the probability of a nuclear accident;
- is valid for small values of the branching process continuation probability, that is, for rather large times after the conditions \( k > 1 \) for the nuclear accident initiation arise;
- overestimates the probability for the branching process to stop and, accordingly, underestimates the probability for a nuclear accident to initiate (see Fig. 1).

As nuclear accidents are rapid processes, and the probabilities for these to initiate should be estimated conservatively, it becomes clear that the preferred way to estimate the probability of a nuclear accident is to use the general model built herein.

**References**