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UNKNOWN ADDITIONAL DELAYED NEUTRON SOURCE IN THE IBR-2 REACTOR

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Шабалин Е. П., Петруски И. Р. Е3-2006-46
Неизвестный дополнительный источник запаздывающих нейтронов в реакторе ИБР-2

Обнаруженная во время пуска реактора ИБР-2 с новым подвижным отражателем решетчатого типа нетипичная асимметрия формы импульса мощности объясняется неизвестным дополнительным источником запаздывающих нейтронов. Сделан расчет интенсивности и временной зависимости этого источника и обсуждается его происхождение. Высказывается предположение о запаздывающем на несколько миллисекунд делении плутония с вероятностью порядка 10^{-6} или наличии короткоживущих запаздывающих нейтронов от деления изотопов америция.

Работа выполнена в Лаборатории нейтронной физики им. И. М. Франка ОИЯИ.

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Shabalin E. P., Petrusky I. R. E3-2006-46
Unknown Additional Delayed Neutron Source in the IBR-2 Reactor

Discovered during the start-up of the reactor IBR-2, with the new reflector, unusual asymmetry of the power pulse can be explained by unknown additional delayed neutron source. The calculation is carried out to characterize both amount and time dependence of this source. A suggestion is made that delayed fission of plutonium with several milliseconds decay or delayed neutrons from fission of americium isotopes is occurring with a probability of the order of 10^{-6}.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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INTRODUCTION

Unlike constant power reactors, the IBR-2 is working in pulsating mode, generating 5 pulses per second. Fast neutron pulse shape theoretically should be practically symmetrical; deviation from symmetry does not exceed 7% (due to accumulation of delayed neutrons during the pulse) [1]. In physical start-up of the reactor with the new moving reflector, significant asymmetry of the fast neutron pulse was detected, see Fig. 1. [2]. The reason for such an asymmetry can be due to additional fissions in fuel either by thermal neutrons coming from remote parts of the reactor surroundings (water in the jacket of the moving reflector, for example) or unknown, short-lived delayed neutrons.

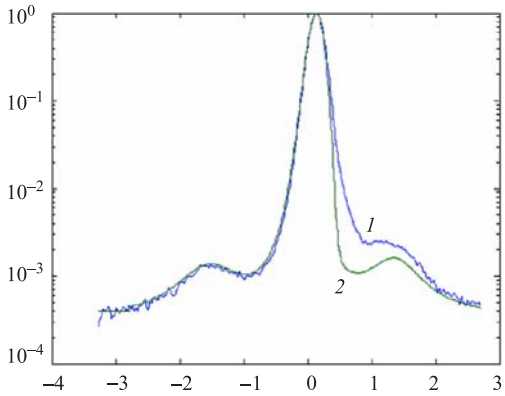

Fig. 1. Measured (*1*) and calculated (*2*) reactor pulse of the IBR-2 reactor with PO-3 moving reflector. Abscissa axis is time in ms, axis of ordinates is equivalent to $N(t)$ used in the text

Notwithstanding the nature of this asymmetry, challenge was formulated to determine the additional neutron source (additional delayed neutrons) in the reactor. To achieve this, a single point reactor kinetics model has been used to simulate kinetics of the IBR-2 reactor as explained in Sec. 1. There is also presented the result of pulse shape calculation. In Sec. 2 additional neutron source is calculated and the model approximating its decay is presented. Concluding remarks can be found in Sec. 3 of this paper.

1. METHOD OF ANALYSIS AND CALCULATION OF PULSE SHAPE

1.1. Point Reactor Kinetics Model for the IBR-2. Standard single point reactor kinetics model was used to model the IBR-2 reactor. Validity of the model is beyond question because pulse shape was measured at low level of the mean power of the reactor. The model and applicable constants are shown below in Eqs. (1), (2) and Tables 1 and 2.

Table 1. Decay constants for delayed neutron sources for ^{239}Pu

Group number	Decay constant s^{-1}	Group fraction
1	0.0129	0.038
2	0.0311	0.280
3	0.1310	0.216
4	0.3310	0.328
5	1.2600	0.103
6	3.2100	0.035

Table 2. Parameters of the IBR-2

Type of parameter	Symbol in Eq. (1)	Parameters value
Mean neutron lifetime	Λ	63 ns
Total fraction of delayed neutrons	β	0.002165

$$\frac{dN}{dt} = \left[\frac{\rho(t) - \beta}{\Lambda}\right] \cdot N(t) + \sum_{i=1}^{6} [\lambda i \cdot Ci(t)], \tag{1}$$

$$\frac{dCi}{dt} = \frac{\beta i}{\Lambda} N(t) - \lambda i \cdot Ci(t), \quad i = 1 \ldots 6. \tag{1a}$$

It is important to notice that the reactivity in Eq. (1) is a function of time; it is discussed in Subsec. 1.2.

1.2. Reactivity Function. The reactivity of the reactor as a function of time can be evaluated from experimental reactivity curve of the moving reflector as it measured in subcritical state of the reactor [2] by transforming position of the reflector onto time and adding some portion of reactivity (let's name it «vertical shift»). The value of the vertical shift and therefore the maximum value of the reactivity function are calculated from criticality condition. An iterative approach is used as described in the later sections, to find critical condition and maximum value of the reactivity function.

The measured reactivity versus position of the moving reflector has been measured for 24 different positions of the reflector. In Fig. 2 the measured data

can be seen, as well the cosine fit to the measured data. Equation 2 shows the reactivity approximating function; coefficients for this fit are listed in Table 3.

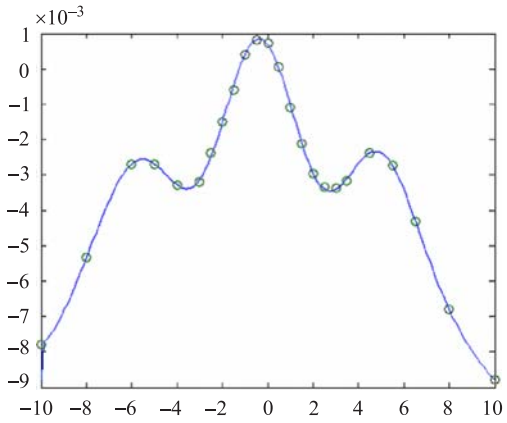

Fig. 2. Reactivity in parts of K_{eff} versus position of the moving reflector (measurement at subcritical state of the reactor with «reversed multiplication» method and shifted up to critical state). Abscissa axis is displacement of the main moving reflector OPO from the position of maximum reactivity

Table 3. Coefficients of cosine fit to reactivity data

N	a_n	b_n	c_n
1	–0.2102	1.005	0.344
2	0.2371	0.9976	0.9431
3	0.9538	0.02869	–1.132
4	0.4027	0.2619	1.078
5	0.01018	0.7763	0.0631
6	–0.4205	0.1109	–0.2349
7	–0.04554	1.358	–1.246
8	–0.07212	0.4511	0.3974

$$ro(x) = \begin{cases} (a_1 \cdot \sin(b_1 \cdot x + c_1) + a_2 \cdot \sin(b_2 \cdot x + c_2) + a_3 \cdot \sin(b_3 \cdot x + c_3) + \\ a_4 \cdot \sin(b_4 \cdot x + c_4) + a_5 \cdot \sin(b_5 \cdot x + c_5) + a_6 \cdot \sin(b_6 \cdot x + c_6) + \\ a_7 \cdot \sin(b_7 \cdot x + c_7) + a_8 \cdot \sin(b_8 \cdot x + c_8)) \cdot 10^{-2} + D \\ \qquad\qquad \text{for} \quad -10^\circ \leqslant x \leqslant 10^\circ, \\ -0.012200 + D \quad \text{for} \quad -10^\circ \geqslant x \geqslant 10^\circ. \end{cases} \tag{2}$$

In Eq. (2) the parameter D corresponds to the unknown *vertical shift* of the reactivity function, value of which is calculated from the criticality condition.

1.3. Numerical Integration Optimization. To integrate system (1), Euler's method of numerical integration was used. The choice of using Euler's method instead of Runge–Kutta has been made mostly because of simplicity of Euler's method and availability of computing power to carry out the calculations in reasonable time interval. The integration was carried out using two different step lengths, one for integration during the impulse and the larger one to integrate the system (1) outside of impulse. To determine the correct step sizes for integration an arbitrary value was chosen for a vertical shift of the reactivity function and the integration results were checked for consistency. The correct choices for integration step sizes can be seen from Table 4.

Table 4. Integration step optimization

Large step		Small step	
Step size	Relative error	Step size	Relative error
0.0001	10.5481	0.0001	0.1265
0.001	10.5480	0.00001	0.12437
0.01	–0.7717	0.000005	0.12425
Small step = 0.00001 ms		Large step = 0.001 ms	

It is important to note that the value of relative error is irrelevant since correct vertical reactivity shift is unknown; the deciding factor is the consistency of relative error values.

1.4. Criticality Search. By integrating system (1) several times with different values of vertical shift in the reactivity function, the criticality search was carried out. Numerical and visual inspections were used to determine the criticality condition. To allow the delayed neutron sources to level out the integration of system (1) had to be done on an extended time interval. To determine whether the system is critical the maximum values of 100^{th} and 1000^{th} peaks were compared and relative error between both was used as the criticality parameter. Results of several runs are shown in Table 5, from which it is clear that the maximum of the true reactivity function must be 0.0030007 (it corresponds to maximum prompt neutron reactivity in a pulse equal to 0.000842).

Table 5. Results of criticality search

Maximum reactivity	Relative error, %
0.0030133	2.184
0.0030123	1.874
0.0030023	0.136
0.0030005	0.003
0.0029998	–0.075
0.0029973	–0.240

Using the true reactivity function the theoretical pulse shape was calculated. As can be seen in Fig. 1, the measured neutron count very well agrees with the predicted pulse shape other then in the region where the additional neutron source is suspected to exist. The difference between measured and calculated $N(t)$ can be seen in Fig. 3.

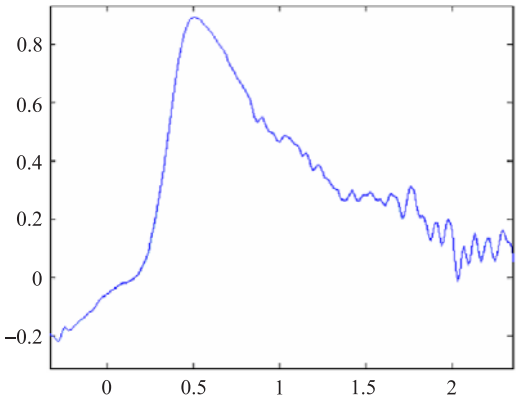

Fig. 3. Relative difference in $N(t) : (N_{\mathrm{exp}}(t) - N_{\mathrm{calc}}(t))/N_{\mathrm{exp}}(t) = S_{\mathrm{th}}/(S_{\mathrm{th}} + S_{\mathrm{delayed}})$. Abscissa axis is time in msec, axis of ordinates is relative difference in $N(t)$

2. EVALUATION OF THE ADDITIONAL DELAYED NEUTRON SOURCE

Additional delayed neutron source is evaluated for an equation like (1a), where $N(t)$ replaced with (N_{exp}–N_{calc}), see Fig. 3, and real delayed neutron source is replaced with unknown $S(t)$. Result is shown in Fig. 4. It is important to realize that the source is in units of neutrons per millisecond; hence the source having comparable maximum value to the neutron count itself is permissible.

In Fig. 5 source to power ratio is shown. It is interesting to notice that the maximum value of the source to power ratio is approximately 0.02 and it is also of interest to fit a function to the fall of the source to provide some insight into the origin of the source. After isolating the fall of the source from the rest of the data an exponential fit has been made as shown in Fig. 6.

The data in Fig. 6 has been shifted in such a way that the maximum value of the source corresponds to time equal zero. The fit to the data has the form

$$f(t) = 1.539 \cdot \mathrm{e}^{-5.899t} + 0.0255 \cdot \mathrm{e}^{-0.4664\mathrm{t}}. \tag{3}$$

It is also of interest to calculate the integral contribution of the source to the $N(t)$, from which one could determine the fraction of the additional delayed neutrons

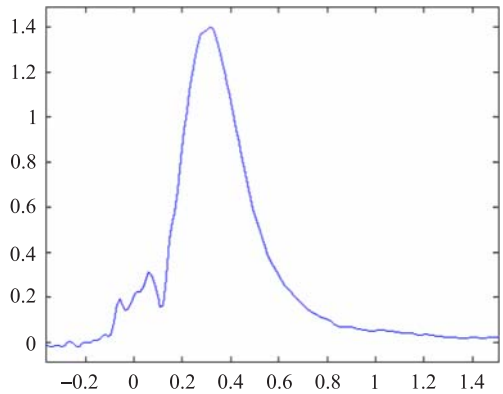

Fig. 4. Additional delayed neutron source calculated. Abscissa axis is time in ms, axis of ordinates is $S(t)$

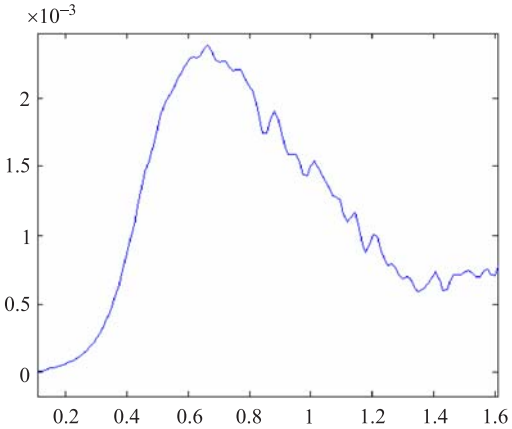

Fig. 5. Source to power ratio. Abscissa axis is time in ms, axis of ordinates is source to power ratio

in the core. Using Eq. (3) the fraction of additional delayed neutrons in the core was determined to be

$$\beta x = \frac{\Lambda \cdot \int_0^\infty S(t)\,dt \cdot 10^3}{\int_0^\infty N(t)\,dt} = 6.11\mathrm{E}-5.$$

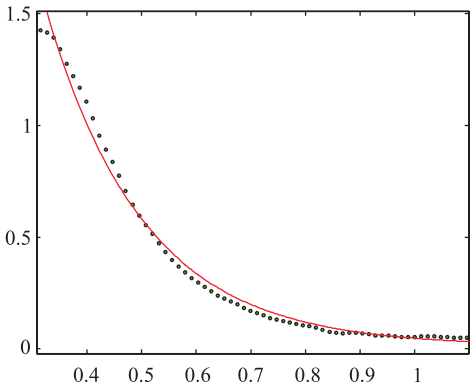

Fig. 6. Exponential part of the additional source (points) and fitting (smooth curve). Abscissa axis is time in ms, axis of ordinates is $S(t)$

3. CONCLUDING REMARKS

As it follows from Eq. (3), time dependence of the additional neutron source is close to the sum of two exponents. Decay time of the first one is 170 μs, and of the second one — about 2.1 ms. Absolute fraction of the additional «delayed» neutrons appeared to be as low as 6.1 10^{-5}, that is, 2.8% of the fission delayed neutrons. Nevertheless, they take an important part in building up a tail of the power pulse due to short decay times.

What is an origin of the additional neutron source? Judging on their parameters, it seems most reasonable to make a conclusion that they are *thermal neutrons* penetrating into the reactor core from outside. Mean transport time of the thermal neutrons from outer water moderators up to the reactor core is estimated to be approximately 130–150 μs that matches well the decay time of the «fast» group of the additional «delayed» neutrons. If this supposition is right, then one can easy calculate probability of thermal neutrons from moderators to reach the core : this is equal to $4.7{\cdot}10^{-5}$/ 0.05 $\approx 1.2{\cdot}10^{-3}$, where 0.05 is leakage of thermal neutrons from moderators relative to all neutrons generating in the core. Probability of an order of 10^{-3} seems to be reasonable value.

Slow fraction of the additional neutrons is only 17% of the fast fraction, or 10^{-6} of absolute fraction. They might be thermal neutrons from water which cools moving reflector jacket, or neutrons reflecting from the surroundings, so-called «room neutrons». If so, their path to the core seems to be too long (about 4 m). Another origin cannot be excluded, for example, neutrons from hypothetical delayed fission of plutonium or delayed neutrons from fission of americium isotopes.

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