THE THERMAL NEUTRON WAVES EXCITATION IN MULTIPLIED MEDIA BOUNDED BY ABSORBER

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An excitation of neutron waves by an external wave source in the active zone of the neutron field is investigated. It is found that the forced neutron waves are transformed into proper (eigen) neutron waves on the borders of the active area. The practical applications of results in noise diagnostics of active area of nuclear reactor are discussed.

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1. INTRODUCTION

The safety of nuclear energy is one of the most actual problems of the day. Diagnostics of the reactor active zone is of importance here, and, in particular, noise diagnostics of neutron flux oscillations, which reflect acoustic and thermal vibrations in the equipment of the active zone and first loop as well as properly of the coolant and moderator.

The neutron-acoustic and neutron-thermal models of diagnostics of nuclear reactors active zone are being intensively developed [1-4] (other references see in paper [5] in this issue). Different in practical orientation, these works represent engineering developments which remain to some degree formal without analytical description based on the equations of physical kinetics [6]. Pioneer researches of Fermi [7] and studies of other authors [8−10] were conducted, however, on the basis of general physics [6] principles.

It is of interest, therefore, to study the noise diagnostics at the level of physical description and strictness. Because neutron detectors reveal noises in the neutron flux (and neutron density) variations, as well as the thermocouples do in the reactor thermal field, a question arises about the nature of such modulation of the neutron and thermal fluxes.

An acoustic wave or other external source wave can modulate the neutron field in the reactor active zone. Here we confine ourselves to the problem of modulation of neutron field by the external source wave in the first coolant loop in the one-dimensional model of planar geometry. Early works on this subject (see [11] and ref. therein) employed a different approach and led to the results which were applied to the measurement of various absorbers characteristics.

The obtained solution of the problem of neutron field modulation by a running wave from the external source can be easily complemented by the solution for an external wave running in the opposite direction. The sum of these solutions, as is generally known, is a standing wave. And, naturally, a solution for a neutron field modulation by waves of complex spectral composition can be obtained within the linear approach by means of superposition of external waves with their proper weights.

2. INITIAL EQUATIONS AND FORMULATION OF THE PROBLEM

The density of thermal neutrons in the processes of their reproduction, slowing down, diffusion and capture in the multiplying medium of a nuclear reactor satisfies an integro-differential equation. This equation is transformed in the differential equation of a diffusive type [8]

$$\frac{\partial N}{\partial t} = D\Delta N + \frac{K}{T_c}(1+\tau\,\Delta)N(\vec{r},t) - \frac{1}{T_c}N(\vec{r},t)\,. \quad (1)$$

Here $D = l_{tr}\mathrm{v}/3$ is the coefficient of the diffusion of thermal neutrons, l_{tr} is the transporting free path, v is the average velocity of thermal neutrons; the inverse time of the capture of neutrons is equal $1/T_c = \sum_a N_a \sigma_c^a \mathrm{v}$, where σ_a is the cross section of the capture of neutrons by the nuclei of sort a and N_a is their density. The coefficient of neutrons reproduction $K = \nu\varphi\,\theta$ equals to the product of new neutrons ν appearing on one act of fission and the probability φ for the fast neutron to be slowed down, times the coefficient θ of the use of thermal neutrons, or, in other words, the probability of that the thermal neutron will cause a fission,

$$\theta = \rho_f\sigma_f \big/ \left(\rho_f\sigma_f + \textstyle\sum_a \rho_a\sigma_a\right) \quad (2)$$

(σ_f is the fission cross section, $\rho_{f,a}$ see in Eq. (16) below). The neutron age τ is proportional to the average square of neutron free path and equals $\tau(E) \approx (2/3)l^2 \ln(E_0/E)$, where l is the average neutron free path, $1/l = \sum_a N_a \sigma_s^a(E)$, $\sigma_s^a(E)$ is the scattering cross section of the nuclei of sort a, N_a is their density, E_0 is the energy of fast neutrons, and E is the energy of thermal neutrons.

The system of equations for the density of neutrons in active zone N_i and out of it, N_e, can be written as

$$\partial N_i/\partial t = \left(D + K\tau/T_c\right)\Delta N_i(\vec{r},t) + \frac{K-1}{T_c}N_i(\vec{r},t), \quad (3)$$

$$\partial N_e/\partial t = D\Delta N_e(\vec{r},t) - N_e(\vec{r},t)/T_c \,. \quad (4)$$

The problem that is described by this system of equations consists in the following. An active area lies between two parallel planes with co-ordinates $z = h > 0$ and $z = -h$. The absorber fills the whole space from $-\infty$ to $+\infty$, including the active zone. An external wave excites the neutron field. When this wave, for example, a sound wave, propagates in positive direction from $-\infty$ to $+\infty$, it runs through the active zone. For each of the region in z direction, we find the solution as the sum of two terms $N_i(\vec{r},t) = N_{oi}(\vec{r}) + N_1(\vec{r},t)$ and $N_e(\vec{r},t) = N_{oe}(\vec{r}) + N_2(\vec{r},t)$ with boundary conditions at $z = \pm h$

$$N_i(\pm h,t) = N_e(\pm h,t)\,, \quad (5)$$

$$(\partial N_i/\partial z)\big|_{z=\pm h} = d(\partial N_e/\partial z)\big|_{z=\pm h}\,, \quad (6)$$

where $d = D_e/D_i$ is the ratio of diffusion coefficients for each region, which in what follows we consider equal to unity.

The stationary state solutions of Eqs. (3), (4) is well known for more general geometrical shapes of the active zone, for example, for the «prism, isolated in bases» $z = \pm h$ [8, p. 132]. For further references we will write down the solution for the basic state that is an extreme case solution for the zone of finite transversal dimension [8], when this dimension tends to infinity (formally). The neutron density is searched in the form

$$N_{i0} = A\cos kz\,, |z| \le h\,;\; N_{e0} = B\mathrm{e}^{-|z|q}\,, |z| \ge h\,. \quad (7)$$

Boundary conditions (5) and (6) together with the condition of having the non-zero values of constants A and B yield the relation

$$k\,\mathrm{tg}\,kh = q\,d \quad (8)$$

and the relation between these constants

$$B = A\,\mathrm{e}^{hq}\cos kh\,, \quad (9)$$

where

$$k^2 = \frac{K-1}{T_c D_{\mathrm{eff}}}\,,\; q^2 = \frac{1}{DT_c}\,,\; D_{\mathrm{eff}} = D + K\tau/T_c\,. \quad (10)$$

The relation between parameters (8) serves, for example, for finding the neutron reproduction coefficient K. For small values $hk \ll 1$, neglecting $\tau K/(D_i T_c) \ll 1$, one has

$$K - 1 = d\,L_e/h \equiv d/(qh)\,. \quad (11)$$

3. SOLUTION OF THE PROBLEM OF NEUTRON WAVE EXCITATION

It is convenient to study the neutron density waves writing down the system of equations (3) and (4) in the following form

$$D_{\mathrm{eff}}^{-1}\,\partial N_i/\partial t = \Delta N_i(\vec{r},t) + k^2 N_i(\vec{r},t)\,, \quad (12)$$

$$D^{-1}\,\partial N_e/\partial t = \Delta N_e(\vec{r},t) - q^2 N_e(\vec{r},t)\,. \quad (13)$$

Here the notations are the same as in Eq. (10). The wave numbers k and q can be decomposed:

$$k^2 = k_o^2 + \Delta\rho\frac{\partial k_0^2}{\partial \rho_0}\,,\; q^2 = q_o^2 + \Delta\rho\frac{\partial q_0^2}{\partial \rho_0}\,.$$

Here $k_0 = k(\rho_0)$, $q_0 = q(\rho_0)$ and $\Delta\rho = \rho - \rho_0$. The system of equations for perturbations of the density of neutrons in the active zone and out of it containing the external source of oscillations of the medium mass density $\Delta\rho(\vec{r},t) \equiv \rho - \rho_0$ looks like (the index «0» is omitted at the unperturbed quantities):

$$D_{\mathrm{eff}}^{-1}\,\partial N_1/\partial t = \Delta N_1(\vec{r},t) + k^2 N_1(\vec{r},t)$$
$$+ A k_1^2 \cos kz \cos(\omega t - \xi z)\,, \quad (14)$$

$$D^{-1}\,\partial N_2/\partial t = \Delta N_2(\vec{r},t) - q^2 N_2(\vec{r},t)$$
$$- A q_1^2 \cos qh\, \mathrm{e}^{q(h-|z|)}\cos(\omega t - \xi z)\,. \quad (15)$$

Boundary conditions at $z = \pm h$ are obtained now making the substitutions $N_i \to N_1$ and $N_e \to N_2$ in Eqs. (5) and (6).

The equations (14) and (15) for variations of the coolant and slowing medium densities in dependence of spatial and temporal variables are given in the explicit form. In Eqs. (14) and (15) the solution (7) and the relation (9) between the constants A and B were used. The variations of the medium density are set in the form $\Delta\rho(z,t) = \rho_1\cos(\omega t - \xi z)$, where $\xi = \omega/s$ is the wave number and s is the phase velocity of the external source wave. The inverse capture time depends linear on the average mass density ρ if the nuclei relative concentrations r_a in absorber and fissile mediums are constant

$$1/T_c = \sum_a \sigma_a N_a \mathrm{v} = \rho\sum_a \sigma_a \frac{r_a}{m_a}\mathrm{v}\,,\; r_a = \frac{\rho_a}{\rho}\,. \quad (16)$$

Here notations are the same as in Eq. (1). Perturbing factors k_1^2 and q_1^2, entering equations (14) and (15), have the form:

$$k_1^2 = \rho_1\,\partial k^2/\partial\rho\,,\; q_1^2 = \rho_1\,\partial q^2/\partial\rho\,. \quad (17)$$

The reproduction coefficient K does not depend on variation of the average density ρ

The vibrating absorber present in the active zone can vary density of neutrons. The «construction» of the external source, which influences the neutron field, takes into account such situation, and it is reflected in equations (14), (15) (see (17) also).

Spatial-temporal dependences of the external source in equation (14) were used for finding the partial solution of the equation in active zone, which is equal to

$$N_1^{\mathrm{part}} = \frac{A}{4}k_1^2\mathrm{e}^{iz\xi - i\omega t}\left\{\frac{\mathrm{e}^{ikz}}{\Delta(k)} + \frac{\mathrm{e}^{-ikz}}{\Delta(-k)}\right\} + \mathrm{c.c.}\,, \quad (18)$$

Here complex conjugate terms are marked c.c., and for compactness parameters $\Delta(\pm k)$ are used,

$$\begin{aligned}
&\Delta(\pm k) = \xi^2 \pm 2\xi k - i\omega/D_{\text{eff}} ,\\
&\Delta_e(\pm iq) = \xi^2 \pm 2i\xi q - i\omega/D , \qquad (19)\\
&\delta(\pm\sigma) = \pm\sigma + i\xi + ik , \ \zeta(\pm\xi) = \sigma - q \pm i\xi .
\end{aligned}$$

The parameters $\Delta_e(\pm iq)$ and $\delta(\pm\sigma)$ given above will be used below.

The general solution of the equation (14) contains two complex constants C_1 and C_2 and a complex wave number of proper oscillations of the neutron density, in the active zone, $\mu = \lambda + i\kappa$, $\mu > 0$ and $\kappa > 0$. Its square equals $\mu^2 = k^2 + i\omega/D_{\text{eff}}$ (see other parameters in (10)). The general solution in the active zone is equal

$$N_1^{\text{gen}}(z,t) = C_1 e^{-i\omega t + i\mu z} + C_2 e^{-i\omega t - i\mu z}. \qquad (20)$$

The solution of equation (15) outside the active zone contains a characteristic number which is equal to $\sigma = \sigma(\omega) = \left(q^2 - i/\delta^2\right)^{1/2} = \sigma' + i\sigma''$, $\sigma' > 0$, where

$$\sigma' = q\left(1 + \omega^2/(4D^2q^4)\right)^{1/2}, \ \omega T_c << 1 . \qquad (21)$$

Here $q^2 = 1/(DT_c)$ and $\delta = \sqrt{D/\omega}$.

Let us write down the particular solution (for outer regions), which satisfy zero boundary condition at $z \to \pm\infty$ (without c.c. terms):

$$N_{2\pm}^{\text{part}}(z,t) = -\frac{A}{2} q_1^2 \frac{\cos kh}{\Delta_e(\pm iq)} e^{i\xi z - i\omega t + q(h \mp z)}, \qquad (22)$$

where parameters $\Delta_e(\pm iq)$ are defined in Eq. (19). In these formulas the upper sign applies for the values $z \geq h$ and lower sign for $z \leq -h$.

The general solution of the equation (15) looks like the solution in the active zone $|z| \geq h$

$$N_{2\pm}^{\text{gen}}(z,t) = D_{\pm} e^{-i\omega t \mp \sigma z} + \text{c.c.}, \qquad (23)$$

Here the rule of upper and lower signs works as in the expression (24) and the boundary conditions are taken into account at $|z| \to \infty$.

The boundary condition of the neutrons density continuity at $z = \pm h$ together with the similar conditions of the neutrons diffusive fluxes continuity, which follows from equations (6), brings to four complex equations needed to obtain the constants C_1, C_2, D_+, and D_-. Excluding constants $D_{\pm}$ from these equations we get two equations for constants C_1 and C_2

$$(i\mu \pm \sigma) C_1 e^{\pm\mu h} - (i\mu \mp \sigma) C_2 e^{\pm i\mu h} = -\frac{A}{4} e^{\pm i\xi h}$$
$$\times\left[k_1^2\left(\frac{\delta(\pm\sigma)}{\Delta(k)} e^{\pm ikh} + \frac{\delta(\mp\sigma)}{\Delta(-k)} e^{\mp ikh}\right) \pm q_1^2 \frac{\zeta(\pm\xi)}{\Delta_e(\pm iq)} \cos kh\right]. \qquad (24)$$

Each of these equations with signs $\pm$ and $\mp$ must be read two times, the first time for the upper sign, second time for lower sign.

Constant C_2, limited to the main terms in the expansion after the small parameter, $\operatorname{Re}\exp(i\mu h) = \exp(-h\operatorname{Im}\mu) << 1$, can be found with the upper sign in Eq. (24) and C_1 can be found with the lower sign in Eq. (24), each time omitting terms with one constant and keeping with the other.

Next a supposition will be adopted, which is important for practical applications of sound diagnostics in the active zone of reactor, namely that $\xi << k$. Thus, after neglecting quadratic in ξ terms the expressions $\Delta(k) = 2\xi k - i\omega/D_{\text{eff}}$ and $\Delta(-k) = -\Delta^*(k)$ become complex conjugated (with the change of sign of $\Delta(-k)$), and the formula for the density greatly simplifies.

As a general solution, the expression for the internal densityof the neutrons can be obtained as

$$N_1^{\text{gen}}(z,t) = \frac{A}{4}\frac{e^{i\mu h - i\omega t}}{i\mu - \sigma}\left\{k_1^2\left(e^{iz\mu - ih\xi}\frac{\delta(\sigma)}{\Delta^*(k)} + \text{c.c.}\right)\right.$$
$$\left. + 2q_1^2 \cos kh\left(e^{iz\mu - ih\xi}\frac{\zeta(\xi)}{\Delta_e(-iq)} - \text{c.c.}\right)\right\} + \text{c.c.} \qquad (25)$$

In the limit $\xi \to 0$ factors $\zeta(\xi)/\Delta_e(iq) = \zeta(-\xi)/\Delta_e(-iq) = (\sigma - q)D/(i\omega)$ equal to each other. Expression in the last round brackets in Eq. (25) have been simplified, as well as in the similar expression $\delta(\sigma)/\Delta^*(k) = (\sigma + i\xi + ik)/(2k\xi + i\omega/D_{\text{eff}})$ the quadratic terms in the relative parameter ξ have been also neglected.

4. PHYSICAL RESULTS AND DISCUSSION

The excitation of the neutron field in the active zone under the action of internal and external to zone sources with the frequency ω and the wave number ξ is described by the sum of particular and general solutions. The particular solution (18) after some transformations takes the form

$$N_1^{\text{part}}(z,t) = \frac{A}{2} k_1^2 \sum_{j=1}^{2} N_j \cos\psi_j(z,t), \qquad (26)$$

where A is the maximum background neutron density and the variable phases are equal to $\psi_{1,2}(z,t) = \omega t - z(\xi \pm k) + \theta_{\pm}$. The phase changes $\theta_{\pm}$ can be determined from the equations $N_{1,2}\exp(i\theta_{\pm}) = 1/\Delta(\pm k)$, and the squares of $N_{1,2}$ modules are equal to $N_{1,2}^2 = 1/|\Delta(\pm k)|^2$.

An appearance of two terms in (26) is due to the origin of the neutron field basic state in the active zone. An external source, in particular a sound wave with the wave number $\xi = \omega/s > 0$, modulates the neutron density with the frequency ω and two combinational wave numbers $k + \xi$ and $k - \xi$. As a result two forced neutron waves are exited which propagate without attenuation with effective wave numbers. At $k > \xi$ the second term in the formula (26) describes the wave reflected from the boundary $z = h$ with the velocity $v_{ph} = \omega/(\xi - k) < 0$. At $k < \xi$ it will be the wave with $v_{ph} > 0$, which propagates in the same direction as the modulating wave.

The obtained solution (26) is true only for the active zone region and describes the effective waves or oscillations of the neutron density (only part of the spatial period of the wave is located in the active zone). However, phase correlations are just the same, as in the obtained particular and general solutions.

Another feature in the physical interpretation of the obtained solution can be seen from Eq. (20), presented below in the real form:

$$N_1^{\text{gen}}(z,t) = AN\mathrm{e}^{-kh}\Big\{\mathrm{e}^{-kz}\Big[k_1^2 M\cos\Psi_+\cos(kh+\phi_+)$$
$$+ q_1^2 L\sin(\Psi_+ + \varphi_+)\cos kh\Big]$$
$$+ \mathrm{e}^{kz}\Big[k_1^2 M\cos\Psi_-\cos(kh+\phi_-)$$
$$- q_1^2 L\sin(\Psi_- + \varphi_-)\cos kh\Big]\Big\}. \qquad (27)$$

This expression describes the waves of neutron density excited at the boundary of the active zone by the non-proper neutron waves represented by the solution Eq. (26). The following notations are used in Eq. (27): $\Psi_\pm \equiv \Psi_\pm(z,t) = \omega t \pm \lambda(z \pm h) \mp h\xi - \theta$ are the variable phases of two waves, λ and κ are the real and imaginary parts of wave numbers of proper neutron wave in the active zone, $\mu = \lambda + i\kappa$, $\mu^2 = k^2 + i\omega/D_{\text{eff}}$ (see other notations in Eqs. (10)). Changes of the phases in the relation to the phase of the external source, that ensure the formation of proper neutron waves in the reactor active zone, can be found from the following relations $N\mathrm{e}^{i\theta} = 1/(i\mu - \sigma)$, i. e. $\mathrm{tg}\,\theta = (\mu' - \sigma'')/(\mu'' + \sigma')$, and

$$M\,\mathrm{e}^{i\phi_\pm} = (\sigma' + ik)/(2k\xi \pm \omega/D_{\text{eff}}),$$
$$\mathrm{tg}\phi_\pm = \left(\omega\sigma'/D_{\text{eff}} \mp 2k^2\xi\right)/\left[k(2\sigma'\xi \pm \omega/D_{\text{eff}})\right],$$

where the squares of the modules are equal to:

$$N^2 = 1/\left[(\mu' - \sigma'')^2 + (\mu'' + \sigma')^2\right],$$
$$M^2 = \left(\sigma^2 + (k+\xi)^2\right)/\left(4k^2\xi^2 + \omega^2/D_{\text{eff}}^2\right), \text{ and}$$
$$L_\pm^{i\varphi_\pm} = \pm\left(q - \sigma' + i(\sigma'' \mp \xi)\right)/\left(\xi^2 \mp 2iq\xi - i\omega/D\right).$$

The parameter ξ is arbitrary. Ignoring it to its smallness yields $L_\pm \equiv L^2 = D^2\left[\sigma''^2 + (\sigma' - q)^2\right]/\omega^2$, $\varphi_+ = \varphi$, $\varphi_- = \varphi + \pi$.

At small values $\omega T_c << 1$ real and imaginary parts of the wave number σ' and σ'' are defined in the text after the Eq. (20) and in Eq. (21); in this case the quantities L^2 и $\mathrm{tg}\,\phi$ take the form

$$L^2 = \left(1/4q^2\right)\left(1 + \omega^2 T_c^2/4\right),\ \mathrm{tg}\,\varphi = -2\omega T_c.$$

The expression for the density of neutrons (27) in the region $|z| \le h$ takes into account the damping of the proper neutron waves. Terms with exponent $\exp[-\kappa(z+h)]$ and with harmonic functions of phase Ψ_+, i.e. $\cos\Psi_+$ and $\sin\Psi_+$, describe the evolution of the density of the neutron wave that propagates in the direction of propagation of the source wave which modulates the neutron field. In this sense the proper neutron wave is generated at the entry of the external source wave in the active zone at its boundary $z = -h$.

Similar considerations can be expressed with respect to the terms with the exponential function $\exp[\kappa(z+h)]$, $-h \le z \le h$. These terms describe the evolution of the density of the neutron wave, generated in the vicinity of the boundary of the active zone $z = h$ which propagates and slowly attenuates in the opposite (negative) direction. However, Eq. (27) has not symmetry (or asymmetry) properties relative to replacement $z \to -z$. In the system there is a selected direction of propagation of a running wave from the external source.

The proper neutron wave propagating in the positive direction is localized at the place of its excitation, that is, at the entry of the external source wave into the active zone. The neutron wave propagating in the opposite direction is localized in the region, where the wave of external source goes out from the active zone. Similar statements can be made concerning the excitation of the proper neutron waves inside the active zone by the external source (terms with q_1^2 in Eq. (27)).

We will remind that the resulted solution takes into account the diffusion of thermal neutrons and their capture in the limited medium of active zone and outside of it.

From the obtained general solution inside the active zone, Eq. (27), and the equations for constants together with exponents $D_\pm\exp(\mp\sigma h)$ it is possible to make the judgment about properties of the neutron field outside of the active zone $|z| \ge h$. The density oscillations outside the zone decrease according to the exponential law $\exp[-\mathrm{Re}\sigma(|z| - h)]$, ($\mathrm{Re}\sigma = \sigma'$, see Eq. (21) and the text after Eq. (20)) at that time as the background neutron density decreases according to the law: $\exp(-q(|z| - h))$, $q^2 = 1/(T_c D)$.

5. CONCLUSION

The numerous researches (both theoretical and experimental) have allowed to develop the noise methods of controlling the processes inside reactors. These methods, due to the registration of neutron noises and the fluctuations of temperature, allow to determine the velocity of coolant, the state of the reactor criticality and a number of other parameters (see the engineering aspects of the problem in article [5] in this issue). At the same time, the obtained information sometimes leads to ambiguous interpretation of the observed processes. That is why it is very important to have an idea about the wave processes, which take place both in the active zone and in the whole system of the reactor first coolant loop.

The external (both inside and outside the active zone) sources that are periodic in time and in space excite in the active zone the forced neutron waves at the sources frequency with the properties described above. The forced neutron wave is transformed at the vicinity of active zone boundary in the proper neutron wave. The conclusion about transformation of the forced waves in the proper neutron waves can be of practical importance in the noise diagnostics of the reactor active zone. This effect must be taken into consideration in the analysis of phase shift of the neutron wave recorded by the neutron detectors positioned in the reactor different measuring channels. Such analysis is used to make a conclusion about the nature of the detected neutron flux perturbations, and, in engineering interpretation, about the origin of the excitation sources, to which, e.g., neutron-thermal excitations can be attributed [3,4]. As can be seen from the present paper, it is necessary to take into account also the proper neutron waves which are excited by the external wave sources, e.g., by the external acoustic waves.

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ВОЗБУЖДЕНИЕ ВОЛН ТЕПЛОВЫХ НЕЙТРОНОВ В РАЗМНОЖАЮЩЕЙ СРЕДЕ, ОГРАНИЧЕННОЙ ПОГЛОТИТЕЛЕМ

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Внешний волновой источник возбуждает вынужденные нейтронные волны в активной зоне нейтронного поля. Эти волны преобразовываются в собственные нейтронные волны на границе активной зоны. Результаты имеют практические приложения в шумовой диагностике активной зоны реактора.

ЗБУДЖЕННЯ ХВИЛЬ ТЕПЛОВИХ НЕЙТРОНІВ В РОЗМНОЖУЮЧОМУ СЕРЕДОВИЩІ, ОБМЕЖЕНОМУ ПОГЛИНАЧЕМ

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Зовнішнє хвильове джерело збуджує примусові нейтронні хвилі в активній зоні нейтронного поля. Ці хвилі перетворюються у власні нейтронні хвилі на межі активної зони. Результати мають практичні застосування в шумовій діагностиці активної зони реактора.