DETERMINATION OF THE EXTERNAL SLUG EFFECT IN MULTIPLYING SYSTEMS WITH A HEAVY WATER MODERATOR

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The external slug effect has been determined in a heavy water multiplying system by measuring the thermal and epithermal neutron densities in a lattice cell. For the systems studied, the external slug effect and the neutron density distribution over the cell determined experimentally and by calculation are found to be in good agreement. Experiments have shown an appreciable slug effect for epithermal neutrons.

In designing heterogeneous reactors, an important role is played by the external slug effect, which determines the thermal utilization. The purpose of the present work is to make an experimental determination of the external slug effect and compare the values with those calculated for a natural uranium reactor with rod type fuel elements, and a heavy water moderator [1].

Experiment

The external slug effect was determined experimentally by measuring the neutron density distribution in the moderator. The measurements were made in the test cell of a heavy water reactor with rod type fuel elements. The external slug effect was investigated for both thermal and epithermal neutrons, the thermal neutron detectors being dysprosium disks, 0.42 cm in diameter, with a dysprosium density of ~ 3 mg/cm^2, while the epithermal neutron detectors were indium disks of the same diameter, with an indium density of ~ 25 mg/cm^2, covered on both sides with ~ 0.025 cm of cadmium. In determining the neutron density distribution, the detectors, wrapped in a plastic film ~ 0.005 cm thick, were put into the moderator, and held in place there on aluminum foil, 0.015 cm thick. The relative detector activity was measured on the apparatus described in [2]. Figure 1 shows the location of the detectors for a lattice with 26 cm spacing, and type 100/0.252* tubes. The detectors were similarly located in other types of lattices but covered 1/8 (1-15), rather than half of the cell, being located around the tube closest to the center, in a plane halfway along with length of the tube.

Figure 2 shows the neutron density distribution for a lattice with 26 cm spacing, and type 100/0.252 tubes. The figure gives the thermal neutron density distribution averaged for points at the same points in the cell and measured according to the scheme of Fig. 1 at a plane halfway down, and two planes higher up, around a tube 36.8 cm from the axis of the active zone. Further, the distribution is given for a plane halfway down the tube but in a cell on the periphery (the distance between the axis of the active zone and the axis of the tube where the measurements were made is 110.3 cm). The epithermal neutron density distribution is also given for four planes at different distances along the tube, measured according to the scheme of Fig. 1 (points 1-5, 10, 14, 13, 12, 11).

All the experimental results used to plot the graphs and calculate the external slug effect were corrected for dropoff in density towards the edge of the active zone as given by a Bessel function.

Table 1 gives values of the external slug effect for different lattice spacings and tube types, as obtained from the experimental data, together with the calculated values. Table 2 gives the experimental value of the external slug effect for thermal and epithermal neutrons, obtained from the results of measurements at different parts of the active zone for a lattice with 26 cm spacing and type 100/0.252 tubes.

* The construction of the tubes and the system of notation are described in [2].

TABLE 1. Experimental and Calculated Values of the External Slug Effect, $W = \overline{N}_{mod}/N_0$

Type of tube	Values of slug effect	Lattice spacing, cm			
		21	23	26	29
100/0.208	W_{exp}	1.331	1.385	1.484	1.513
	W_{calc}	1.328	1.374	1.437	1.497
	W_{dif}	1.269	1.315	1.378	1.435
100/0.252	W_{exp}	1.345	Not found	1.514*	Not found
	W_{calc}	1.379	" "	1.504	" "
	W_{dif}	1.310	" "	1.435	" "
112/0.230	W_{exp}	Not found	1.393	1.496	1.552
	W_{calc}	" "	1.416	1.496	1.571
	W_{dif}	" "	1.349	1.420	1.503
112/0.252	W_{exp}	Not found	1.411	1.505	1.573
	W_{calc}	" "	1.450	1.535	1.615
	W_{dif}	" "	1.378	1.462	1.540

Notes: 1) $W = \overline{N}_{mod}/N_0$, where $\overline{N}_{mod}$ is the mean neutron density in the moderator, and N_0 is the mean thermal neutron density on the outside surface of the process tube, around which the measurements were made, normalized to $N_0 = 1$. 2) W_{exp} is the experimental slug effect. 3) W_{calc} is the value calculated from Eqs. (1)-(3). 4) W_{dif}, from Eqs. (1), (2) (in terms of q_{1dif}). 5) Accuracy of the experimental values, ± 0.03; for the case marked with the *, the accuracy is ± 0.015.

TABLE 2. External Slug Effect as a Function of Point of Measurement for a Lattice with 26 cm Spacing and Type 100/0.252 tube

Distance along the tube from the center of the active zone to the plane where the measurements were made	Distance from tube axes to center of active zone, cm		
	36.8	110.3	36.8
	Thermal neutrons		Epithermal neutrons
0	1.514±0.015	1.503±0.015	1.079 ± 0.02
40	1.523±0.015	—	1.082 ± 0.02
70	1.499±0.015	—	1.078 ± 0.02
90	—	—	1.078 ± 0.02

Comparison of the Experimental and Calculated Values of the External Slug Effect

1. Simple formulas are given in [3, 4] for the slug effect, corrected for the error in the diffusion approximation and giving good accuracy (of the order of the P_3 approximation of the spherical harmonic method). The ratio of the mean density in the moderator to the mean density at the inside surface of the moderator is equal to [5]:

$$W = \frac{\overline{N}_{mod}}{N_0} = 1 + \frac{q_1}{q_{hom} QR}, \tag{1}$$

where $q_{hom} = V_{mod}\, l_{\alpha U}/V_U l_{mod}$ (V_U is the uranium area, and V_{mod} is the moderator area), Q is the self shielding factor, and R is the neutron density jump in the gap. The experimental data of [6] was used in calculating the values of Q and R. Further, $q_1 = q_{l\,dif} + \Delta q_1$. For a square lattice

$$q_{1\,dif} = \frac{a^2}{4\pi L^2_{mod}}\left(\frac{\ln\frac{1}{\varepsilon}}{1-\varepsilon} - \frac{3}{2} + \frac{1}{2}\varepsilon\right), \tag{2}$$

where a^2 is the area of the cell, L_{mod} is the diffusion length in the moderator, and $\varepsilon = (a^2 - V_{mod})/a^2$. The nondiffusion correction, Δq_1, is of the form [3, 4]

$$\Delta q_1 = \frac{V_{mod}}{4\pi l^2_{max}}\delta. \tag{3}$$

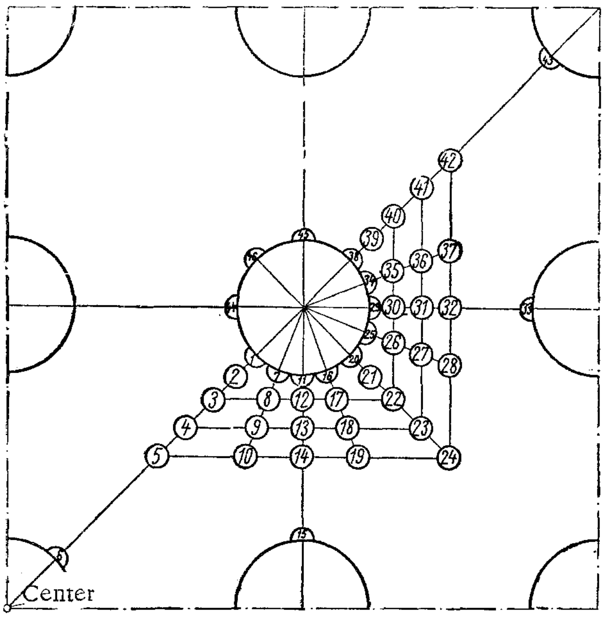

Fig. 1. Location of foils for measurements in a lattice with 26 cm spacing and type 100/252 tubes.

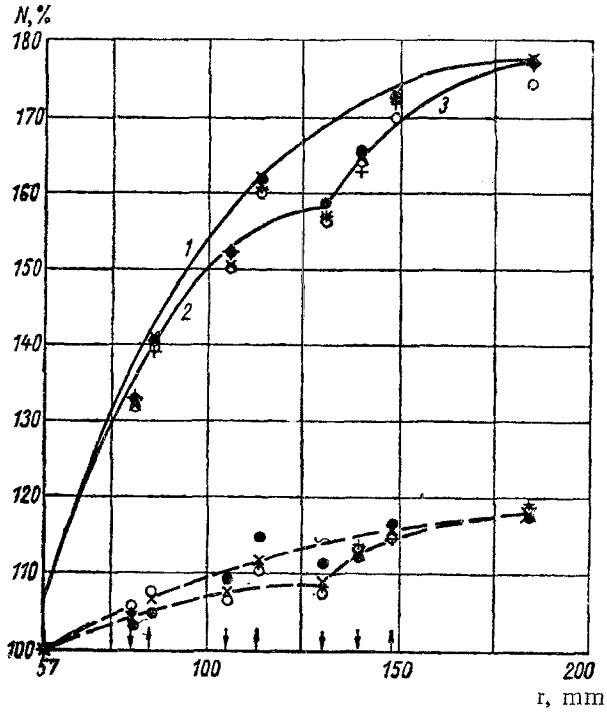

Fig. 2. Neutron density distribution N in lattice cell with 26 cm spacing and type 100/0.252 tubes: X) in a plane halfway into the active zone; O) in a plane 40 cm above the middle of the active zone; ●) in a plane 70 cm above the center of the active zone; +) epithermal distribution in a plane 90 cm above the middle of the active zone, and thermal neutron distribution in the center of the active zone around a tube 110.3 cm from the axes. The arrows show to which curve the experimental points above them refer. The errors in the experimental points and curves are ± 2% for thermal neutrons (upper group of curves) and ± 4% for epithermal neutrons (lower group of curves). In the foil location diagram, curve 1 corresponds with points 1-5, curve 2 with points 11-14, and curve 3 with points 14, 10, 5.

Here, $\delta = 2\frac{l_{tr}}{\rho}(\lambda - \frac{2}{3})$ where l_{tr} is the transport length in the moderator, ρ is the radius of the slug (including the gap), and λ is the black body boundary condition [7]. Table 1 gives the values of W_{calc} and W_{dif}, calculated using q_1 and q_{1dif} respectively (1). In the present case, the correction Δq_1 is small and amounts to ~ 15% of q_1. It may be seen from the table that the values of W_{calc} are in better agreement with the experiment than the values of W_{dif}.

2. The neutron density distribution in the moderator may be described from the results of [8], where use was made of the theory of functions of a complex variable, with the assumption that there is no absorption in the moderator. In order to correct for the error in the diffusion approximation at the surface of the slug, a jump may be introduced at the surface of the slug corresponding with the nondiffusion correction to the external slug effect [3, 4].

The solution obtained in [8] we shall write in the following way:

$$N(x, y) = A[N_{max} - \psi(x, y)], \tag{4}$$

where A is a normalization constant. For a square lattice

$$N_{max} = (1-\varepsilon)\left(\frac{1}{\mu} - \ln 2\sqrt{\pi\varepsilon} + \frac{1}{2}\varepsilon + \frac{\pi}{6} + 2e^{-2\pi}\right) + \frac{\pi}{12} + 0{,}082900 + e^{-2\pi}. \tag{5}$$

The quantity $1/\mu$ describes the neutron sink and is equal to

$$\frac{1}{\mu}=\frac{2l_{tr}\,QRl_{aU}}{3\varrho^2}+\frac{\delta}{2}, \tag{6}$$

where δ is given by Eq. (3).

The function $\psi(x, y)$ in (4) is given by the equation

$$\psi(x, y)=-\operatorname{Re}\ln\theta_1(e^{-\pi}, z)+\\+\frac{\pi y^2}{a^2}+0{,}082900, \tag{7}$$

where $z = x/a + i\,y/a$, and Re is the real part of the function. For the directions shown in Fig. 2, the function $\psi(x, y)$ is written in the following way:

Curve 1

$$\psi(x, 0)=-\ln\theta_1\left(e^{-\pi}, \frac{x}{a}\right)+0{,}082900;$$

Curve 2

$$\psi\left(\frac{a}{2}, y\right)=-\ln\theta_4\left(e^{-\pi}, \frac{y}{a}\right)+0{,}082900;$$

Curve 3

$$\psi(r)=-\ln\left[\theta_1\left(e^{-\pi}, \frac{r}{a\sqrt{2}}\right)\theta_3\left(e^{-\pi}, \frac{r}{a\sqrt{2}}\right)\right]-\\-0{,}180770,$$

where θ_1, θ_3, and θ_4 are theta functions.

The jump in density at the surface of the slug may be expressed in terms of the quantities μ and δ:

$$\Delta N_0=-\mu\frac{\delta}{2}. \tag{8}$$

The case marked with the* in Table 1 gives the following values:

$$(AN_{max})_{exp}=(AN_{max})_{calc}=1{,}779;\quad A_{calc}=1{,}132;$$
$$N_{0\,exp}=1;\ N_{0\,calc}=1{,}066\ \text{[From (4)]};$$
$$\Delta N_0=-0{,}064;\ N_{0\,calc}+\Delta N_0=1{,}002.$$

It may be seem from Fig. 2 that the calculated curve is in good agreement with the experimental density curve.

The following conclusions may be drawn from the material presented above:

1. For the types of lattice considered, the external slug effect found experimentally is in good agreement with the calculated values [3, 4, 8].

2. There is an appreciable external slug effect for the epithermal neutrons.

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