and the oxygen (n, α) reaction. The values of λ were calculated for deuterium and oxygen from Emmerich's data. The formula for λ in group n given by Amster (*5*) simplifies to

$$\lambda_n = \sigma_s^n(T_{00}^2 + T_{01}^2 \overline{\mu_c^n})/\xi\sigma_s^n$$

where

σ_s^n and $\xi\sigma_s^n$ are the nth group zeroth Legendre coefficients of the σ_s and $\xi\sigma_s$,

T_{00}^2 and T_{01}^2 are coefficients defined by Hurwitz and Zweifel (*8*), having the values 0.4236 and -0.8157, and

$\overline{\mu_c^n}$ is the average value of the cosine of the center of mass scattering angle in group n.

Figure 1 shows the excellent agreement between the MUFT 4 code in its Grenling-Goertzel approximation (modified by the addition of a $\partial\lambda/\partial u$ term) and Wade's experiments. The dashed curve shows much poorer agreement for the ordinary age theory results.

REFERENCES

1. J. W. Wade, "Neutron Age in Mixtures of Light and Heavy Water," DP-163 (1956).
2. R. L. Hellens, "Neutron Slowing Down in Group Diffusion Theory," WAPD-114 (1956).
3. H. Bohl, Jr., E. M. Gelbard, and G. H. Ryan, "MUFT-4 Fast Neutron Spectrum Code for the IBM-704," WAPD-TM-72 (1957).
4. E. Grueling, F. Clark, and G. Goertzel, "A Multigroup Approximation to the Boltzmann Equation for Critical Reactors," NDA 10-96 (1956).
5. H. J. Amster, *J. Appl. Phys.* **29**, 623 (1958).
6. W. S. Emmerich and J. B. Weddell, "Multigroup Neutron Cross Sections," Westinghouse Research Report 6-94511-6-R16 (1957).
7. W. S. Emmerich, "Multigroup Neutron Data for Deuterium," Westinghouse Research Report 410FF323-R1 (1958).
8. H. Hurwitz and P. F. Zweifel, *J. Appl. Phys.* **26**, 923 (1955).

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The Slowing-Down Spectrum in a Heterogeneous Reactor

The $1/E$-form for the slowing-down neutron spectrum derived from an infinite homogeneous model neglecting resonance capture, is often applied to heterogeneous reactors. This letter is concerned with deviations from the $1/E$-form that occur in rod-type reactors as a result of the heterogeneous nature of the fission sources. These deviations will increase with increasing neutron energy and also with increasing lattice pitch. The magnitude of the departure from $1/E$ has been measured in a ZEEP (*1*) lattice cell with and without a natural uranium rod and has been compared with predictions from age diffusion theory. The calculations are similar to those performed by Tralli *et al.* (*2*) for complete lattices.

The slowing-down spectrum was measured at four energies by measuring the specific activities induced under 0.076-cm thick cadmium in the foils described in Table I.

In the first two detectors in the Table most of the capture occurs near the listed resonance energy, although small contributions occur in higher-energy resonances and in $1/v$ capture just above the cadmium cutoff at 0.5 ev. The results have not been corrected for these effects. In manganese, however, approximately one-half of the epi-cadmium capture occurs just above the cadmium cutoff. For this reason a method employing resonance self-shielding was developed which permitted the separate measurement of the 337-ev flux. A manganese foil was irradiated inside a manganese cover of 0.013 cm thickness which itself was enclosed in cadmium. The difference in specific activity between the manganese cover and manganese foil is proportional to the 337-ev flux.

Contributions from the higher resonances are not negligible in the case of the uranium detectors. For foils of the thickness used, the contribution from the 6.7-ev level is approximately 43%, from the 21-ev level is 23%, and from the 37-ev level is 15% in a $1/E$ spectrum.

The measurements were performed in the central cell of ZEEP on a horizontal line passing through the neighboring rods. The rods (*1*) were immersed in heavy water at a hexagonal spacing of 24.1 cm and consisted of bundles of 19 uranium oxide cylinders of diameter 1.32 cm. The points in Fig. 1 show the experimental flux distributions obtained at the four energies in Table I. The counting errors are all less than 1%, except for the case of the manganese difference which are shown in Fig. 1. Additional errors of approximately 2% for indium, 1% for gold, and 5% for uranium occur due to variations in thickness and composition of the foils and the resulting variations in self-shielding. The upper distributions in Fig. 1 were obtained with the central rod in place, the lower distributions with the rod removed. The "rod-in" and "rod-out" experimental points for a given resonance detector are normalized to the same flux at a reference position in the reflector of ZEEP.

The curves shown in Fig. 1 are predictions of the flux per unit lethargy from age-diffusion theory with 19 energy groups and an infinite reactor. The radial distribution of fissions in the rod based on the measured distribution (3) of thermal neutrons was included in the calculation. Four energy groups were used to describe the fission spectrum. Resonance capture and inelastic scattering in uranium were not included in the calculation. The "rod-in" curves in Fig. 1 were obtained using an equivalent cylindrical cell with zero slope for all fluxes at the cell boundary. The "rod-out" curves in Fig. 1 were calculated by subtracting the fluxes obtained from a single rod in infinite heavy water from the fluxes with the rod in. It was assumed that the fission sources in adjacent rods remained the same when the central rod was withdrawn.

The experimental "rod-in" values for each detector were normalized to the appropriate theoretical "rod-in" curves, and the same normalization factors were applied to the experimental "rod-out" values. In the case of the 337-ev flux, the average value of the flux measured with the rod in was used in the normalization. In the case of In, Au and U^{238}, the flux distributions were expected to dip

TABLE I

RESONANCE DETECTORS

Detector	Resonance energy (ev)	Foil material	Thickness (cm)	γ-activity counted	Corresponding theoretical group (ev)
Indium	1.46	99.8% Pb-0.2% In	0.01	54 min In^{116}	1.1-3.0
Gold	4.9	100% Au	0.0025	2.70 day Au^{198}	3.0-8.3
Uranium	6.7 & up	80% Al-20% U^{238}	0.005	2.33 day Np^{239}	
Manganese subtraction	337	89% Mn-11% Ni	0.013	2.58 hr Mn^{56}	170-450

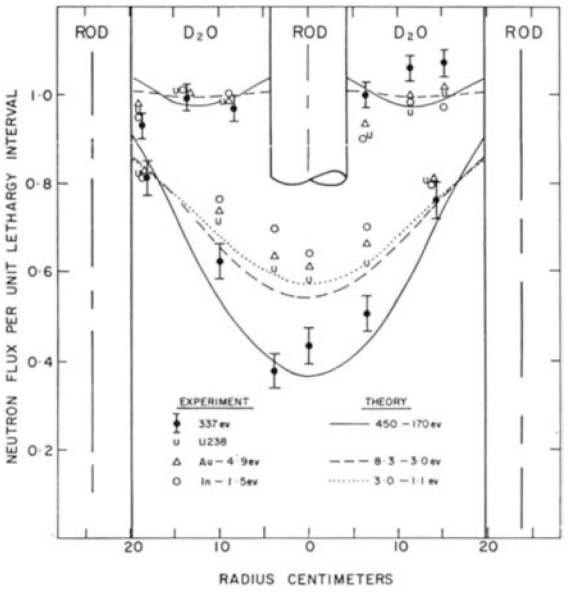

FIG. 1. Epithermal neutron distributions measured in the central cell of ZEEP at four different energies with (upper points) and without (lower points) the central rod in place. The curves are the predictions from age diffusion theory for energy groups corresponding to the experimental points. Where points are grouped together they were all obtained at the same radius.

near the rod because of resonance capture in the rod, and this was confirmed by Fig. 1 and other experiments. Since resonance capture was omitted from the theory the normalization in these cases was done at a point midway between rods.

The agreement between experiment and theory is considered satisfactory. The asymmetries in the experimental points with the rod in were probably caused by misalignment of the central rod and foil holders. The theory appears to overestimate the depression of the flux with the rod out in the region below 8.3 ev. This discrepancy is in the same direction and of similar magnitude to that expected to be caused by neglecting resonance capture in the calculation.

The results show that large distortions may occur in the slowing-down spectrum. Substantial errors can result from using empty lattice or reflector positions to measure resonance integrals in the region of a few hundred ev, the resonance integral being underestimated if the gold resonance integral is used as a standard. The same error occurs in the measurement of the Doppler effect in cadmium-covered uranium since the fission sources are removed. The error in this case is large since the Doppler region extends up to several kev.

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REFERENCES

1. D. W. HONE, E. CRITOPH, M. F. DURET, R. E. GREEN, A. OKAZAKI, R. M. PEARCE, AND L. PEASE, *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* P/212, 12, 351.
2. N. TRALLI, J. AGRESTA, AND W. SEIBYL, *Nuclear Sci. Eng.* **6**, 157–158 (1959).
3. R. E. GREEN, Rept. No. UK/C6/109, AECL Chalk River 1957.

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Some Studies of Aqueous Uranium Oxide Slurries[1]

Aqueous slurries of uranium compounds offer some promise as reactor fuels; the purpose of this letter is to point out that the preparation of such slurries in concentrations sufficiently great and of sufficient stability to be of interest as fuels offers an excellent illustration of colloid principles.

The sedimentation velocity of spheres, of radius r, density d in a solvent of viscosity η, density d_s under gravity, is given by the classical sedimentation velocity equation

$$V(\text{cm/sec}) = \frac{2}{9} r^2 \frac{(d - d_s)g}{\eta}$$

[1] Contribution No. 779. Work was performed in the Ames Laboratory of the U.S. Atomic Energy Commission during the period 1950–1952; this work was earlier summarized in two AEC reports, namely, ISC-145 (1951) and ISC-194 (1952), classified "Secret" at dates of issue. This area has been recently declassified.