to use this poisoning effect for the calibration of our coarse control rod bank. In fact we consider the reactivity value of the coarse control rod bank obtained from the comparison with xenon poisoning the most reliable value (*6*).

REFERENCES

1. S. GLASSTONE AND M. C. EDLUND, "The Elements of Nuclear Reactor Theory." Van Nostrand, Princeton, New Jersey, 1952.
2. R. L. MURRAY, "Nuclear Reactor Physics." Prentice Hall, Englewood Cliffs, New Jersey, 1957.
3. A. M. WEINBERG AND E. P. WIGNER, "The Physical Theory of Neutron Chain Reactors." Univ. of Chicago Press, Chicago, Illinois, 1958.
4. W. HÄLG, S. RAVANI, H. ALBERS, AND Z. J. DORON, *Z. angew. Math. u. Physik* **14,** (1963).
5. H. K. CLARK AND J. C. ENGLISH, Xenon tables. DP-200 (May 1957).
6. H. ALBERS, Z. J. DORON, AND T. GOZANI, *Neue Technik*, **4,** 461 (1962).

H. ALBERS
AND Z. J. DORON*

Swiss Federal Institute for Reactor Research
Würenlingen, Switzerland

W. HÄLG
AND S. RAVANI

Swiss Federal Institute of Technology
Zurich, Switzerland

Received July 10, 1962
Revised November 19, 1962

* Z. J. Doron is on leave from the Israel Atomic Energy Commission.

Nonperturbing Foils—An Experimental Verification*

Neutron detecting foils which have the capability of measuring thermal neutron flux without introducing flux perturbation have been proposed in an earlier publication (*1*) which presented the theory of the nonperturbing foils and gave preliminary experimental verification. The method is intended for use in regions where the thermal flux is due to a uniform slowing down source. A double P_0 calculation indicates that the nonperturbing condition exists when the moderating ratio of the foil equals that of the medium in which the measurement is performed. This matching condition establishes foil parameters such that the ratio of the production rate of thermal neutrons which slow down in the foil to the absorption rate of the foil is equal to that of the medium. It is felt that there is sufficient promise in this technique to warrant an accurate verification that these foils cause no perturbation. It is the purpose of this article to present experimental data substantiating the nonperturbing nature of these foils.

To accomplish this verification, two methods are used. The first, and most direct, is to show that foils whose thicknesses vary by a factor of four yield the same specific activity. The other method is to show that the specific activity of these foils is equal to the unperturbed value as determined by an extrapolation method for metal foils.

The medium selected for this experimental investigation was water. The test section consisted of a triangular array of 1-curie neutron sources with the test section in the geometric center. This assembly is described in detail in ref. *2*. The test section provided a thermal flux which was spatially invariant over ±5.3 mean free paths in water in the horizontal plane and ±2.7 mean free paths in the vertical plane. Thus, the unperturbed flux through the region occupied by the foils remained constant in spite of the wide variation in foil thickness.

For ease of fabrication, the matching foils were prepared in liquid form. The foil material used consisted of a solution of 99.8% D_2O and 0.2% H_2O, and which contained 2.90 gm/liter of metallic indium in the form of indium nitrate. This solution has a moderating ratio equal to that of water. The high D_2O concentration was used to allow the maximum concentration of indium since the flux in the test section was low. The cylindrical liquid foil containers were fabricated from $\frac{1}{16}$ in. thick lucite with an internal diameter of 2 cm and thicknesses from $\frac{1}{16}$ in. to $\frac{1}{4}$ in. The metal foils were also fabricated 2 cm in diameter with thicknesses that ranged from 0.0006 in. to 0.005 in. All of the foils were supported on mylar or polyethylene tape attached to $1\frac{3}{4}$ in. lucite rings. Cadmium covers, 0.040 in. thick, were fabricated for all foils.

The metal foils were activated in the test section and counted at the center of two 2 in. x 2 in. NaI(Tl) crystals spaced 2 cm apart. It was experimentally verified that this assembly eliminated geometry and self-absorption variations due to changes in foil thickness. This assembly was also used to determine the "unperturbed" activity as measured by a $\frac{1}{16}$ in. thick matching foil. It was not convenient to use this counting system for the thicker matching foils since their greater size introduced significant geometry corrections. To reduce the variation in counting efficiencies, these foils were integrally counted in the 1 in. diam well of a $1\frac{3}{4}$ in. diam by 2 in. long NaI(Tl) scintillation crystal. Variation in counting efficiencies and self-absorption between the various foil thicknesses were corrected experimentally by activating some foil material in the AGN-201 reactor and filling the various size foil containers with this material. Each container was then counted in the well crystal and the correction factors obtained. The maximum correction was only 4.2%.

The specific activities of the bare and cadmium covered matching foils are shown in Fig. 1 for thicknesses of $\frac{1}{16}$ in. to $\frac{1}{4}$ in. Each point represents an average of five separate runs. The standard deviation of each point due to counting statistics in less than 0.5%. Straight lines were fitted to these data by the method of least squares. The curve representing activity due to the thermal neutron flux was determined by subtracting the two curves. To allow a close inspection of these results, it is necessary to examine the equations obtained from the analysis. These are

$$\text{Bare} \qquad \frac{A_\infty}{m} = 329.04 - 0.11x \tag{1}$$

$$\text{Cd} \qquad \frac{A_\infty}{m} = 77.07 + 0.77x \tag{2}$$

$$\text{Thermal} \qquad \frac{A_\infty}{m} = 251.97 - 0.88x \tag{3}$$

* This work was supported in part under a research grant from the Texas Engineering Experiment Station.

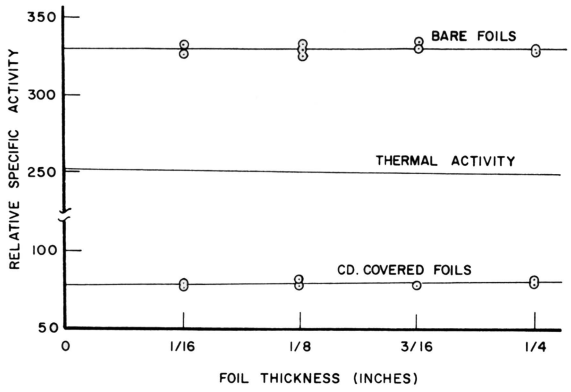

FIG. 1. Specific activity of matching foils as a function of thickness.

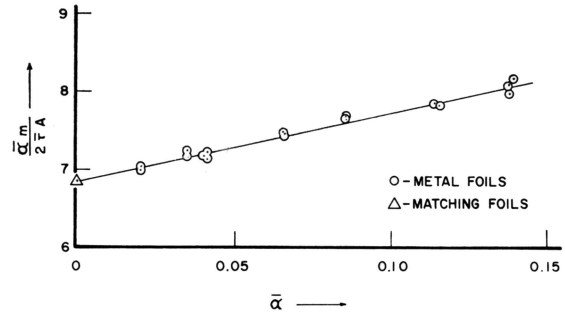

FIG. 2. Determination of unperturbed activity for conventional foils by extrapolation to zero absorption probability.

where x is foil thickness in units of $\frac{1}{16}$ in. Thus, for the thickest foil investigated, i.e., $x = 4$, the activity as given by Eq. (3) is 248.45, or 1.4% less than the activity at zero thickness. It should be noted that Eq. (1) for the bare activity is essentially constant showing a decrease of only 0.13% over the range of thicknesses studied; however, the cadmium covered activity shows an increase of 4% over this range. This trend means a decrease in the cadmium ratio with increasing foil thickness. One would normally expect the cadmium ratio to increase with foil thickness due to self-shielding of the resonance flux. This discrepancy is probably due to the slowing down and absorption, in the thicker foils, of epithermal neutrons which penetrated the cadmium cover.

The extrapolation method for determining the unperturbed activity was effected by plotting $(\bar{\alpha}/2\tau)(m/A)$ vs. $\bar{\alpha}$, where $\bar{\alpha}$ is the absorption probability averaged over the energy and angular distribution, $\bar{\alpha}/2\tau$ is the self-shielding factor and A/m is the observed thermal specific activity. This plotting method yields a linear functional variation which greatly improves the extrapolation procedure (*3*, *4*). A least squares fit was performed on the experimental data shown in Fig. 2 and the $\bar{\alpha} = 0$ intercept was found to be 6.85 gm/cpm with a standard error of estimate of ±0.6%. This extrapolated value, of course, corresponds to the reciprocal of the unperturbed specific activity since the self shielding factor is unity for a zero thickness foil. The value of the reciprocal of the unperturbed specific activity as measured by the $\frac{1}{16}$ in. matching foils was found to be 6.86 gm/cpm. The standard deviation of this point, which was determined as the average of five separate runs, was less than ±0.5% due to counting statistics.

From the results of this experiment, it can be seen that foils with a moderating ratio equal to that of the medium in which they are being activated may be used without producing measurable flux perturbations.

An alternative viewpoint may be considered in discussing the validity of these nonperturbing foils. A more conventional attitude would establish that they approach "zero thickness" and thus cause negligible perturbations. This viewpoint has some merit since the $\frac{1}{16}$ in. thick foils used in this investigation were equivalent in indium content to a indium metal foil 6.3×10^{-5} cm thick. Thus, this technique provides a simple and accurate method of producing extremely thin foils. We prefer the matching concept, however, since it has some theoretical justification for establishing a satisfactory concentration which will yield negligible perturbations. However, it should be noted that the angular and energy distribution of the unperturbed thermal and epithermal fluxes may be affected by the introduction of these foils into the medium which may in turn induce a perturbation.

The theory which established the matching condition used in this study did not adequately describe these second order effects. However, the results of this investigation indicate that these effects probably are not critical if measurements with accuracies of the order of 1% are satisfactory. To better understand this situation, more sophisticated theoretical treatments are required which may modify the matching criterion. It should be noted that these problems are not yet understood for conventional metal foils. If these factors contribute significantly to flux perturbations, it is felt the matching foil concept offers the greatest hope for a convenient, practical solution. Work is presently in progress at this laboratory which should lead to a better understanding of these problems and very possibly lead to more valid matching criteria.

Matching foils can also be fabricated using other activants and in solid forms. Activants such as gold or sodium may be used and beta-gamma coincidence counting techniques employed to determine their absolute activity, and thereby, obtain a direct measurement of the absolute flux.

It is anticipated that these matching foils will see extensive use in standardizing fluxes for various neutron experiments.

We are indebted to Mr. James L. Tallas for his conscientious help in obtaining the data for this study.

REFERENCES

1. J. D. RANDALL AND J. V. WALKER, The elimination of flux perturbation associated with neutron detecting foils. *Nuclear Sci. and Eng.* **11,** 69 (1961).
2. J. V. WALKER, J. D. RANDALL, AND R. C. STINSON, JR., Thermal neutron flux perturbation due to indium foils in water. *Nuclear Sci. and Eng.*, **15,** 309 (1963).
3. C. W. TITTLE, Perturbation of foil activation in thermal neutron fields. *Trans. Am. Nuclear Society* **5,** No. 1, (June 1962).
4. C. W. TITTLE, private communications.

J. D. RANDALL
J. V. WALKER

Department of Nuclear Engineering
A. & M. College of Texas
College Station, Texas
Received October 2, 1962