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RESONANCE ESCAPE PROBABILITY OF A LATTICE OF MULTI-ROD FUEL ELEMENTS

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* Dr. J. Fuller is now with the Physics Department of Baylor University, Waco, Texas.

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ABSTRACT

The resonance escape probability of a square lattice of multi-rod uranium fuel elements in a graphite moderator has been measured by activation techniques. The elements were spaced 9.5 inches apart, center to center. Each element consisted of seven fuel rods 3/4 inches in diameter and 5 feet long containing 2.78 wt-% enriched uranium metal.

The measured value of p is 0.809 ± 0.005. The corresponding value of the effective resonance integral for the element is 7.9 ± 0.3 barns. This value of the effective resonance integral is in agreement with the value obtained at other laboratories for an element of the same surface-to-mass ratio. The results are also in agreement with the resonance integral obtained from an analysis of exponential experiments performed with lattices made up of these same elements.

I. INTRODUCTION

To predict the behavior of a heterogeneous lattice of fuel and moderator it is necessary to compute the effective multiplication factor. This factor is given by the equation

$$k_{eff} = k_{\infty} L ,$$

where k_{eff} is the infinite multiplication factor and L is the neutron non-leakage probability of the system. More explicitly,

$$k_{\infty} = \eta \epsilon p f ,$$

where, for a thermal heterogeneous lattice, η is the number of fast fission neutrons produced per thermal neutron absorbed in the fuel, ϵ is the fast fission factor, p is the resonance escape probability, and f is the thermal utilization. Of these four factors, the resonance escape probability is generally the most difficult to compute accurately.

The methods of computing this factor from the basic cross section data are still in the process of being developed. At present it seems better, wherever possible, to obtain p by direct experiment because, in addition to giving p for a particular lattice of interest, it provides another piece of experimental information with which computed values can be compared. There is a particular need for experimental information on lattices containing multi-rod fuel elements, because the additional geometric complexity of the element introduces a further uncertainty into the calculation of p.

A rather close subcritical mockup of the "dry" sodium-cooled, graphite-moderated reactor experiment was available for which p could be measured directly. The theoretical models describing the SRE and this subcritical lattice are nearly the same. Because of these two facts, it was decided to measure the resonance escape probability of this subcritical assembly in order to furnish a close approximation to this quantity for the SRE and for the purposes of checking the accuracy of the theoretical model used to calculate this quantity for both assemblies. This measurement will be discussed in the following sections.

II. THEORY OF THE MEASUREMENT

The method that has been developed[1] for experimentally determining the resonance escape probability of a heterogeneous lattice containing uranium fuel of low enrichment is briefly described below. The activity resulting from the U^{238} (n, γ) reaction in the fuel is measured. The reaction proceeds as follows:

$$U^{238}(n,\gamma) \longrightarrow U^{239} \xrightarrow[23\ min]{\beta,\gamma} Np^{239} \xrightarrow[2.346\ days]{\beta,\gamma} Pu \xrightarrow{\gamma} .$$

It is the Pu^{239} internal conversion X-ray activity that is measured. Experimentally, this is the activity most easily separable from the others present. It is measured with sets of both bare and cadmium-covered U^{238} foils. The ratio, ρ, of the resonance capture probability of neutrons in the U^{238} to the thermal capture probability is related to the measured activities by

$$\rho = \frac{\overline{A}_{Cd}}{\overline{A}_B - \overline{A}_{Cd}}, \qquad \text{...(1)}$$

where the bars indicate that these activities have been averaged over the fuel and the subscripts B and Cd refer respectively to the activities of the bare and the cadmium covered foils. The ratio ρ can also be expressed in terms of the resonance escape probability by

$$\rho = \frac{1-p}{pfF}, \qquad \text{...(2)}$$

where f is the thermal utilization of the lattice and

$$F = \frac{\Sigma_a^{28}}{\Sigma_a^{28} + \Sigma_a^{25}}$$

The Σ_a's are macroscopic absorption cross sections for the U^{238} and U^{235}. For the 2.78 wt-% enriched fuel of density 18.88 g cm^{-3} used at present, the value of F is 0.1215 ± 0.0018. The resonance escape probability is then determined by experimentally measuring ρ, f, and F. The definition of resonance escape probability implied in this method is

$$p = \frac{Q(E_{th})}{Q(E)} ,$$

where $Q(E)$ is the number of fast neutrons that escape leakage and absorption processes to reach the resonance energy region of the U^{238}, and $Q(E_{th})$ is the member of these neutrons which get below the cadmium cut-off.

III. APPARATUS AND PROCEDURE

The above method has been applied to a subcritical square lattice of uranium loaded elements in a graphite moderator. The lattice was mounted on top of a water boiler reactor thermal column. The square cells of this lattice were 9.5 inches on a side. A horizontal cross section, A, of the lattice and an elevation diagram, B, of the system are shown in Figure 1. Each element consisted of seven fuel rods 3/4 inches in diameter and 5 feet long. These were made from 6-inch-long slugs stacked one on top of the other. A horizontal cross section of a typical element is shown in Figure 2. The central 4 x 4 square array of elements contained rods made of two types of fuel. The lower 4 feet were fueled with uranium metal of 2.78 wt-% enrichment. The upper foot was fueled with natural uranium. The twenty peripheral elements were loaded completely with natural uranium. This buffered lattice arrangement was necessary because of the limited amount of enriched fuel available.

The general procedure adopted in measuring the resonance escape probability in this lattice consisted of the following steps. Foils of U^{238}, both bare and cadmium covered, were exposed at several locations within the fuel. The activities of the foils were determined by means of scintillation counters. From these data, the bare and cadmium covered activities averaged over the volume of the fuel were determined. Some details in each of these steps are presented below.

Foils having dimensions of 10 by 2 by 0.123 mm made from uranium metal with a low U^{235} content (12 ppm) were used to detect the plutonium activity. When inserted in the fuel, these foils were oriented with their long dimension parallel to the axis of the fuel rod and their planes normal to the rod radius. This made it possible to measure details of the neutron flux, since the small dimension of the detector is nearly in the direction of the horizontal component of the flux gradient.

Inserts made of the enriched fuel material were used to hold the uranium foils at specified places in a fuel rod. One of these is shown in detail in Figure 3. As indicated in this figure, the loaded insert can be placed in a slot machined into one end of a fuel slug. When assembled, the centers of foils placed in the

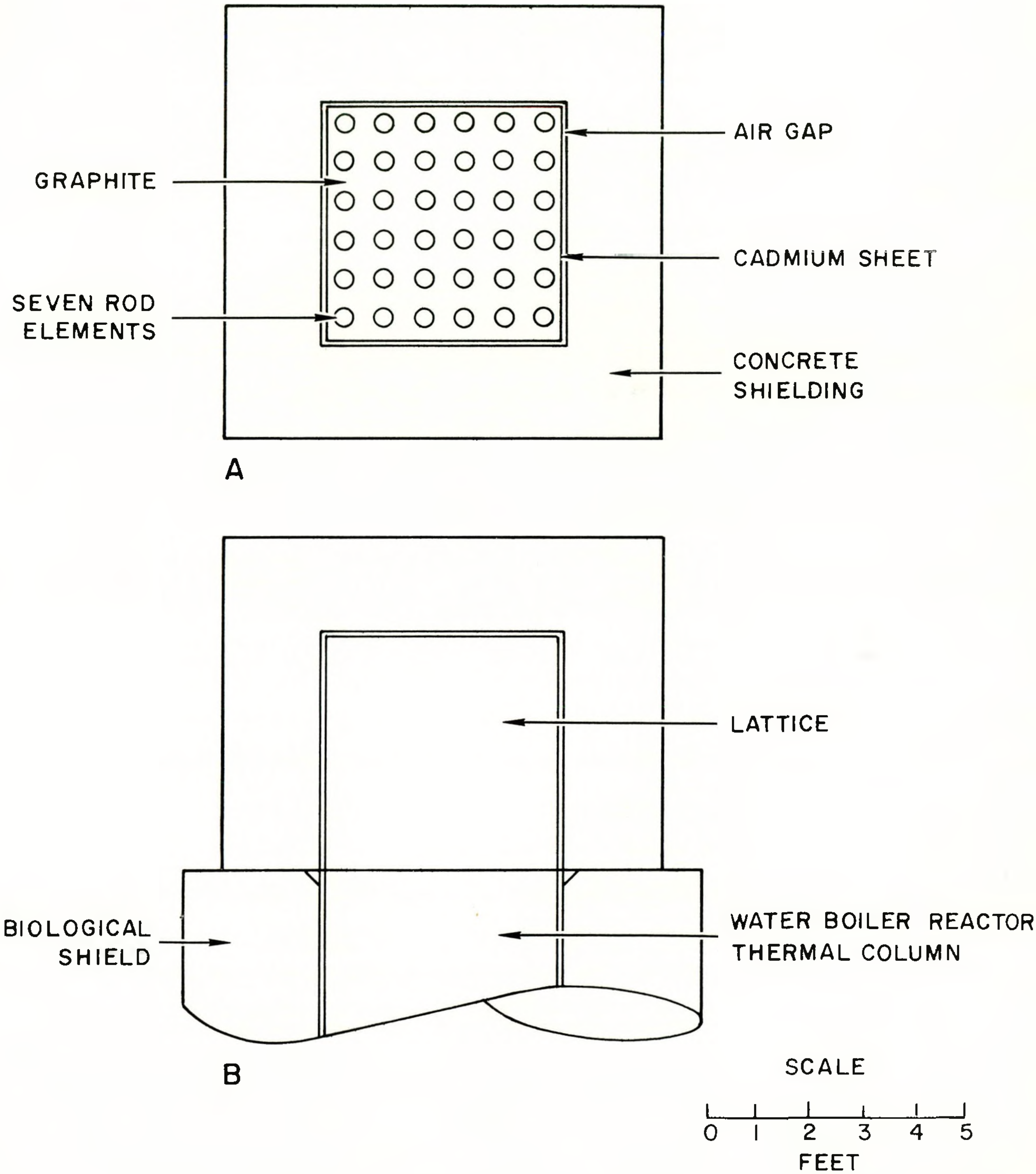

Figure 1. Horizontal and Vertical View of the Lattice

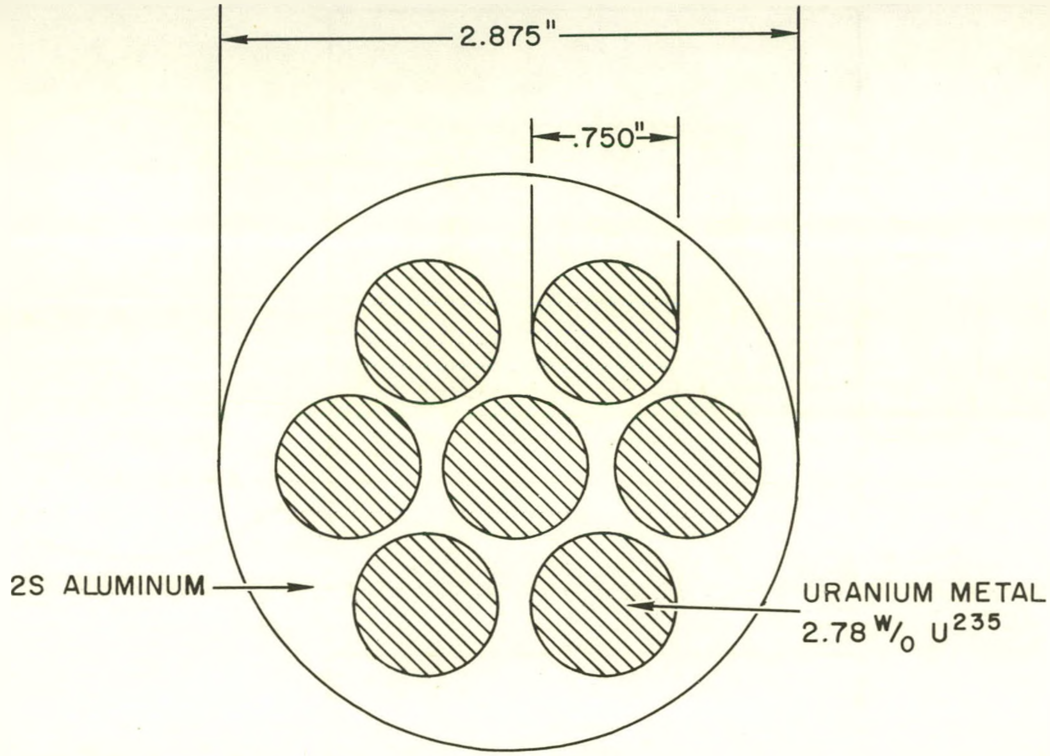

Fig. 2. Horizontal Cross Section of Fuel Element.

slots were aligned along a diameter of the rod. The slotted end was covered by a carefully-machined disc 0.5 cm in thickness to prevent neutrons from streaming directly into the foils.

A similar foil holding arrangement was made for obtaining the cadmium covered activities. In this case, the fuel in the immediate neighborhood of the foils was surrounded by a cylindrical cadmium box as shown in Figure 4.

The foils were exposed in the fuel rods at a distance of 18 inches above the bottom of the assembly where the cadmium ratio no longer varied with height. All exposures were made in two of the central four elements, as shown in Figure 5. It was necessary to take only one bare foil traverse and one cadmium covered foil traverse in the center rods. These two traverses were taken at the same time with the bare and cadmium covered inserts placed in the rods as indicated. Several exposures were necessary to find the bare and cadmium covered activities of the outer rods. As indicated in Figure 5, the same outer rod was used for each irradiation, and during each of these, a single bare foil

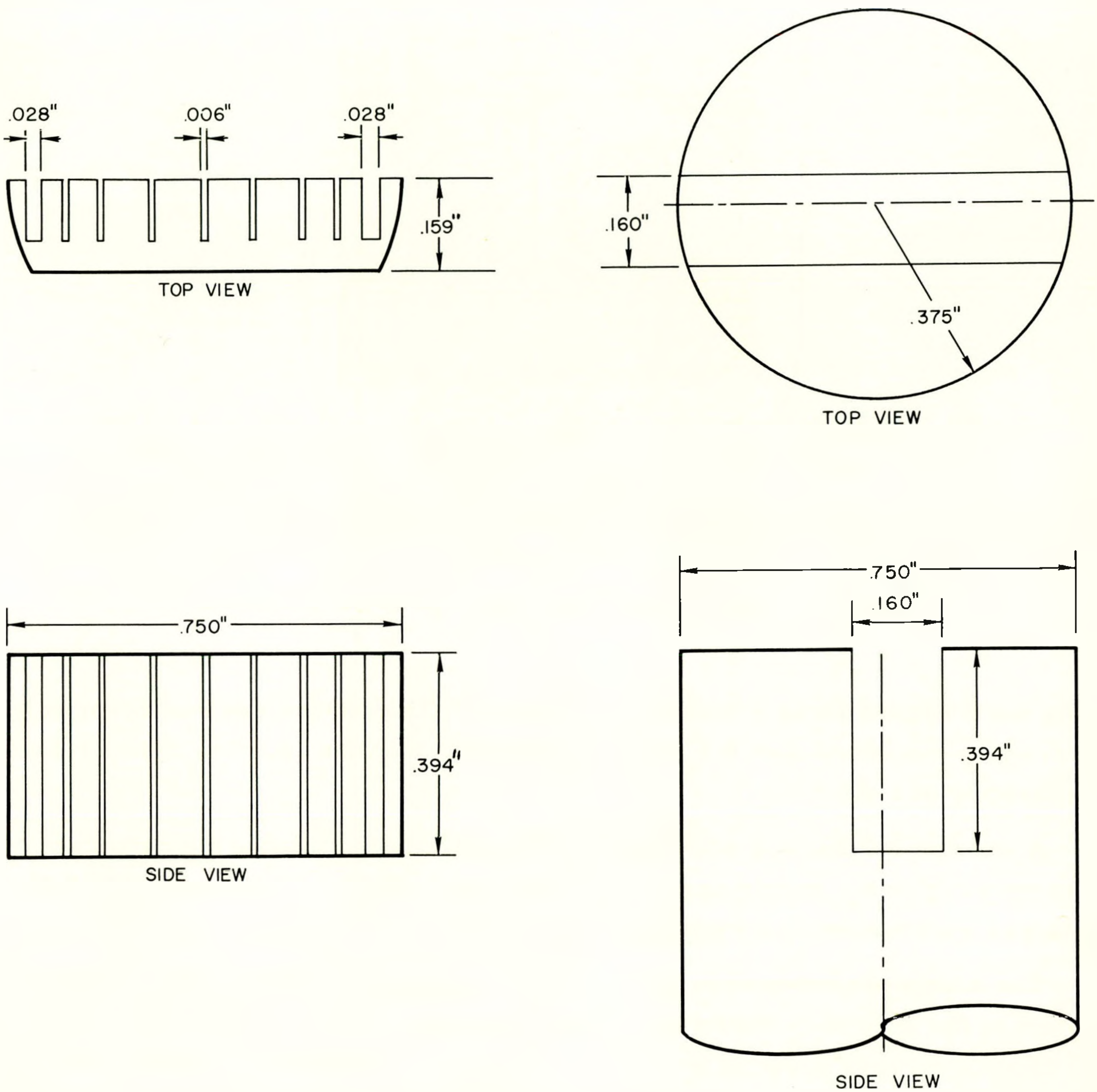

Figure 3. Uranium Foil Holding Inserts (Left) and Carefully Machined Rods to Receive These Inserts (Right)

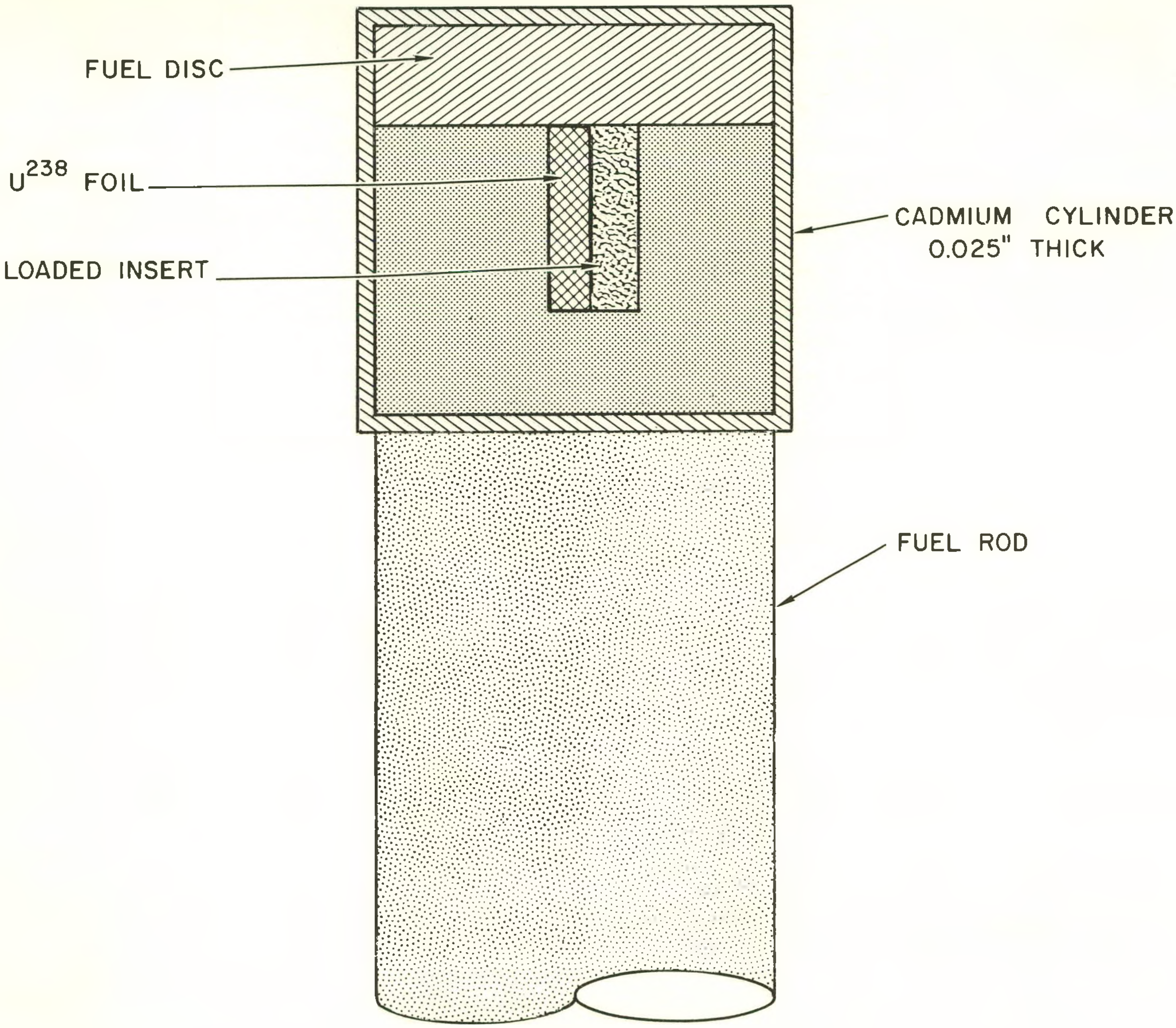

Figure 4. The Arrangement for Obtaining the Cadmium Covered Foil Activity

traverse and single cadmium covered foil traverse were made. Each time, the inserts were positioned so that a bare foil was in a lattice flux which was symmetric with that of a corresponding cadmium covered foil. This step automatically normalized the bare and cadmium covered activities to one another except for slight differences in the masses of the foils which made it necessary that

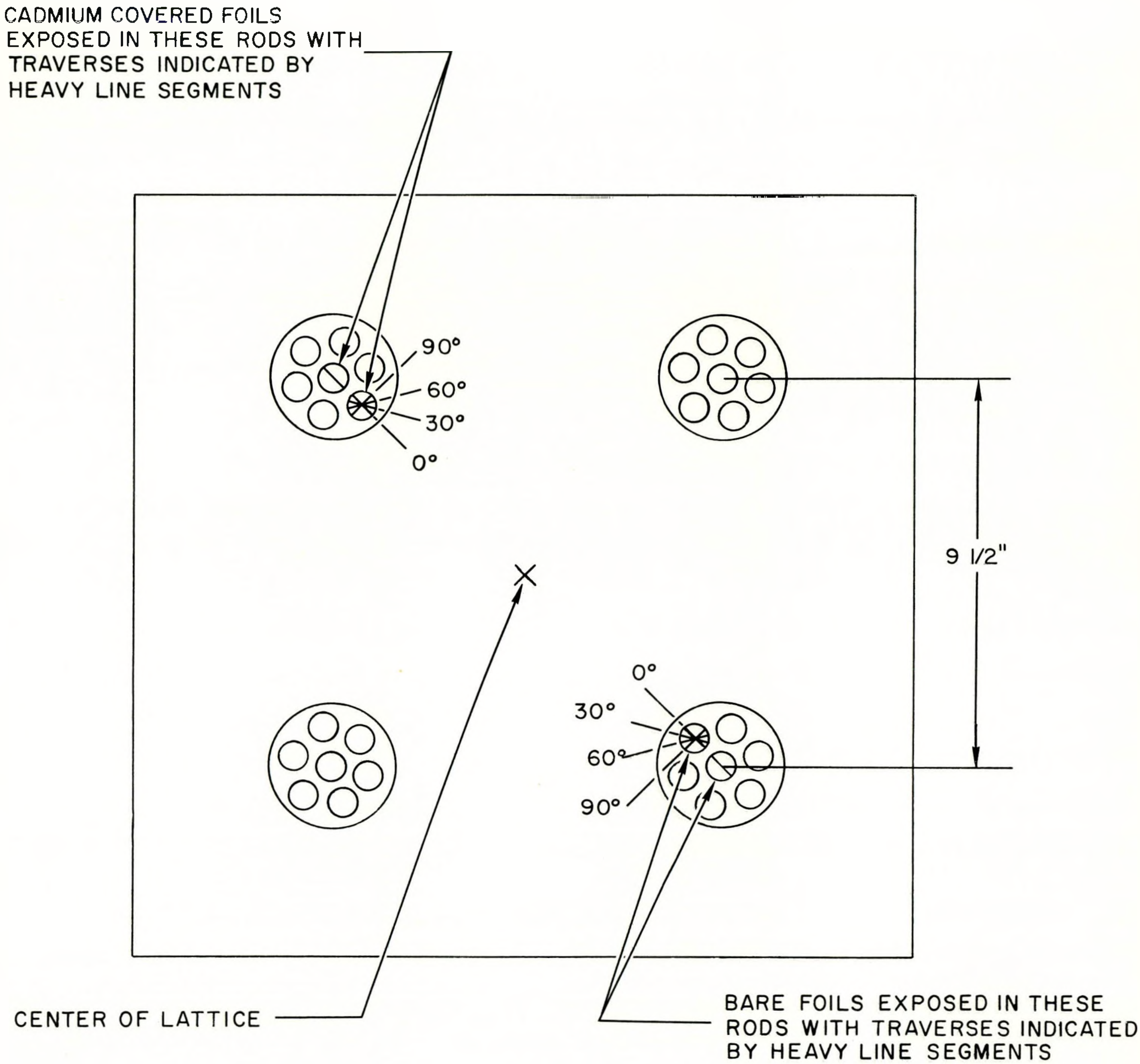

Figure 5. Detail of the Central Portion of the Lattice

each activity be multiplied by an appropriate factor to reduce all data to that which would exist for foils of equal mass. In addition, since the complete distribution could not be determined in one run due to the limited number of foils that could be irradiated in one run, certain foil locations were repeated to provide the means of normalizing the data from one run to another.

After the foils had been irradiated, their activities were measured with a scintillation spectrometer. NaI crystals 1-1/4 inches in diameter and 2 mm thick were used. These crystals were attached to the end faces of Type 9262 Dumont photomultiplier tubes. For a crystal of this thickness, the 100 kev gamma radiation still has a high probability of generating scintillations because of its high attenuation in the crystal material. On the other hand, the background from high energy gamma rays arising from fission products or other sources is reduced because of their much lower attenuation in the crystal.

The spectrometer window, of width 3 volts, was set on the 32.2 kev barium X-rays from this source. To observe the 103 kev radiation from the irradiated uranium foils, the pulse height selector setting was increased by a factor of 103/32.2 = 3.20. This was done rather than positioning the window on the 103 kev radiation itself because other radiations from fission products and naturally active substances were present in the 100 kev region. These background radiations, because of their different half-lives, alter the shape of the radiation peak in this energy region with time.

The initial step in the analysis of the data consisted of the following series of corrections to be applied to the observed 103 kev activities of the U^{238} foils:

1) Subtraction of the background activities consisting of the natural activities of the foils and instrumental background.

2) Correction of the activities to take into account the fact that they were generally of unequal masses. The foils weighed about 50 mg each and were weighed to an accuracy of 0.1%. The correction factor used was that based on taking the activity to be proportional to the mass of the foil. The masses did not differ by more than 15% from the average.

3) Correction of the activities obtained in several irradiations to a common irradiation. In each run there were at least four foils that were always placed in the same location. The multiplicative factors to reduce the data to a common run were determined from the measured activities of these foils.

4) Correction for the horizontal buckling of the assembly. It is assumed that the neutron flux can be expressed as the product of the gross lattice flux and the intra-cell flux.

5) Adjustment of the activities to a common time after reactor shutdown.

The last correction was necessary because all the foils could not be counted during the same time interval after reactor shutdown. It required an accurate knowledge of the half-life of the Np activity. This was determined by observing the activities of two highly irradiated foils over a period of about two weeks. One foil was bare and the other cadmium covered. The activities were determined from observation of the 103 kev radiation. The observed values were 2.38 ± 0.02 and 2.39 ± 0.02 days, respectively. Since these did not differ significantly, an average value of 2.385 ± 0.014 days was used throughout the analysis. The fact that they did not differ significantly indicated that the background from fission product activities due to slow neutron absorption in the small amount of U^{235} present in the foils does not have a measurable influence on the half-life determination. The half-life is somewhat higher than the value quoted by Wish,[2] which indicates that fast fission may be influencing our half-life measurements a little. However, the difference is not enough to introduce a significant systematic error into the final calculation of resonance escape because the ratio, ρ, is not strongly dependent on the half-life.

The presence of the cadmium capsule around the small portion of fuel containing the detector foils would be expected to depress the source of fast neutrons. This effect has been investigated elsewhere[3] and has been found to be negligible.

To obtain the average activities $\overline{A}_{Cd}$ and $\overline{A}_B$ in the fuel, the observed activities were first plotted as shown in Figure 6. These curves effectively give a two-dimensional survey of the neutron flux distributions over a horizontal cross sectional area of the fuel in an element. The average activities can be obtained from this information by graphical integration. The extrapolated portions of the curves, near the fuel rod surface, were determined in each case from a semi-logarithmic plot of the data near the surface. A typical case is shown in Figure 7. The extrapolation is made over at most a distance of 25 mils. With these values of $\overline{A}_{Cd}$ and $\overline{A}_B$, values of ρ and p were determined from equations (1) and (2). These values are given in the table. In these calculations, a value of $f = 0.931 \pm 0.009$, as determined in a previous experiment,[4] was used.

The averaged activities obtained from the graphical integration contain a systematic error due to the fission product activity in the U^{238} foils. This was corrected for in the following way. It was assumed, because of the high depletion in U^{235}, that the fission products in the foils were due to the fast fission of U^{238}. Neutrons with energies equal to or greater than the fast fission threshold are distributed nearly uniformly over the fuel. Hence, it was assumed that the activities of all the foils, after correction for unequal masses, could be expressed as

$$A_D = A_{49} + A_f ,$$

where A_{49} was due to the plutonium buildup and A_f was due to the fission product activity. The value of each factor was considered to be the same for every bare and cadmium covered foil. Schematic plots of A_D, A_{49}, and A_f are shown in Figure 8.

The factor A_f was averaged over the fuel and subtracted from the averaged measured activities in the numerator of equation (1) to correct ρ for this fission product activity of the foils.

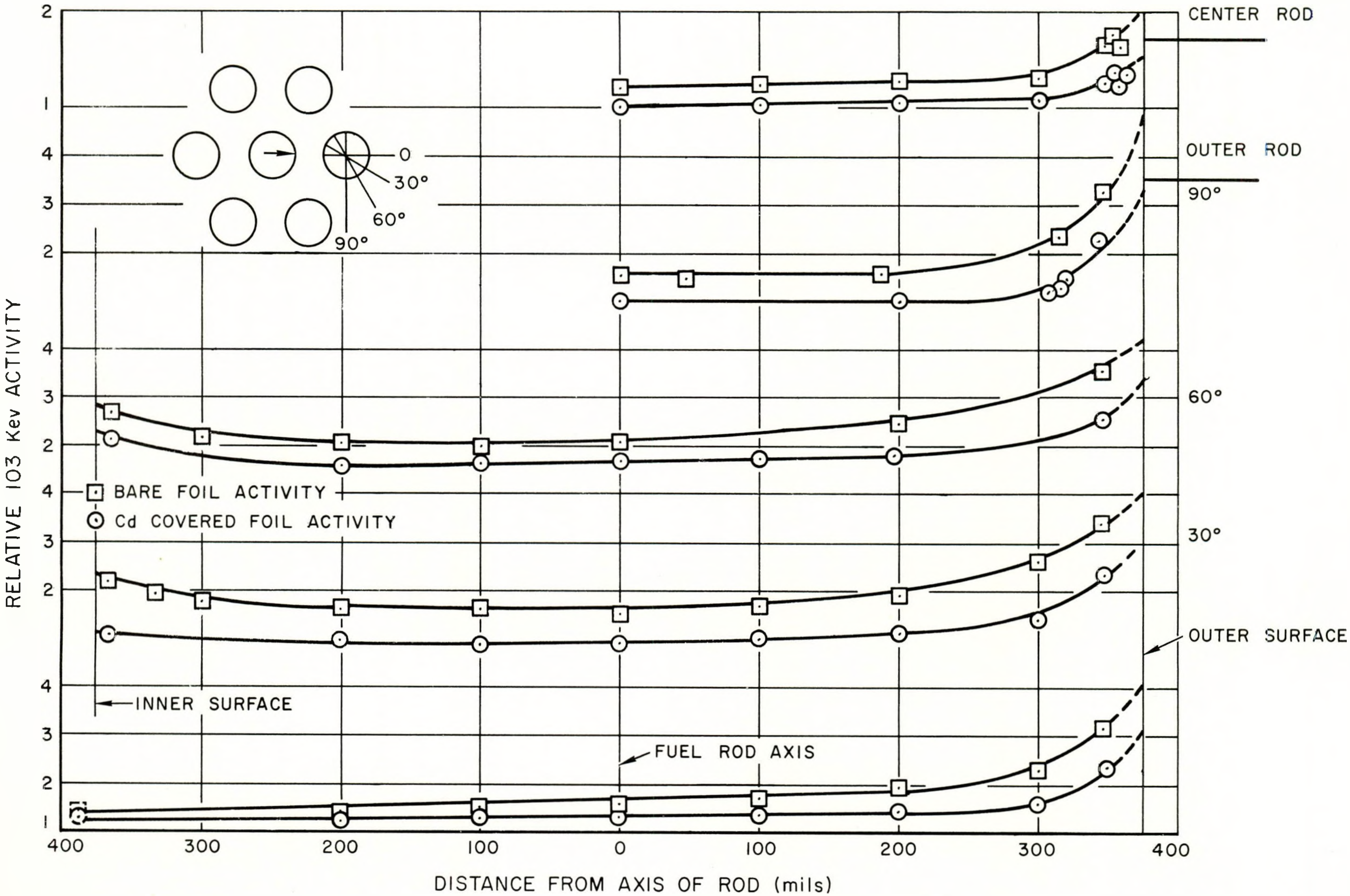

Figure 6. An Effective Two Dimensional Plot of the Bare and Cadmium Covered Foil Activities

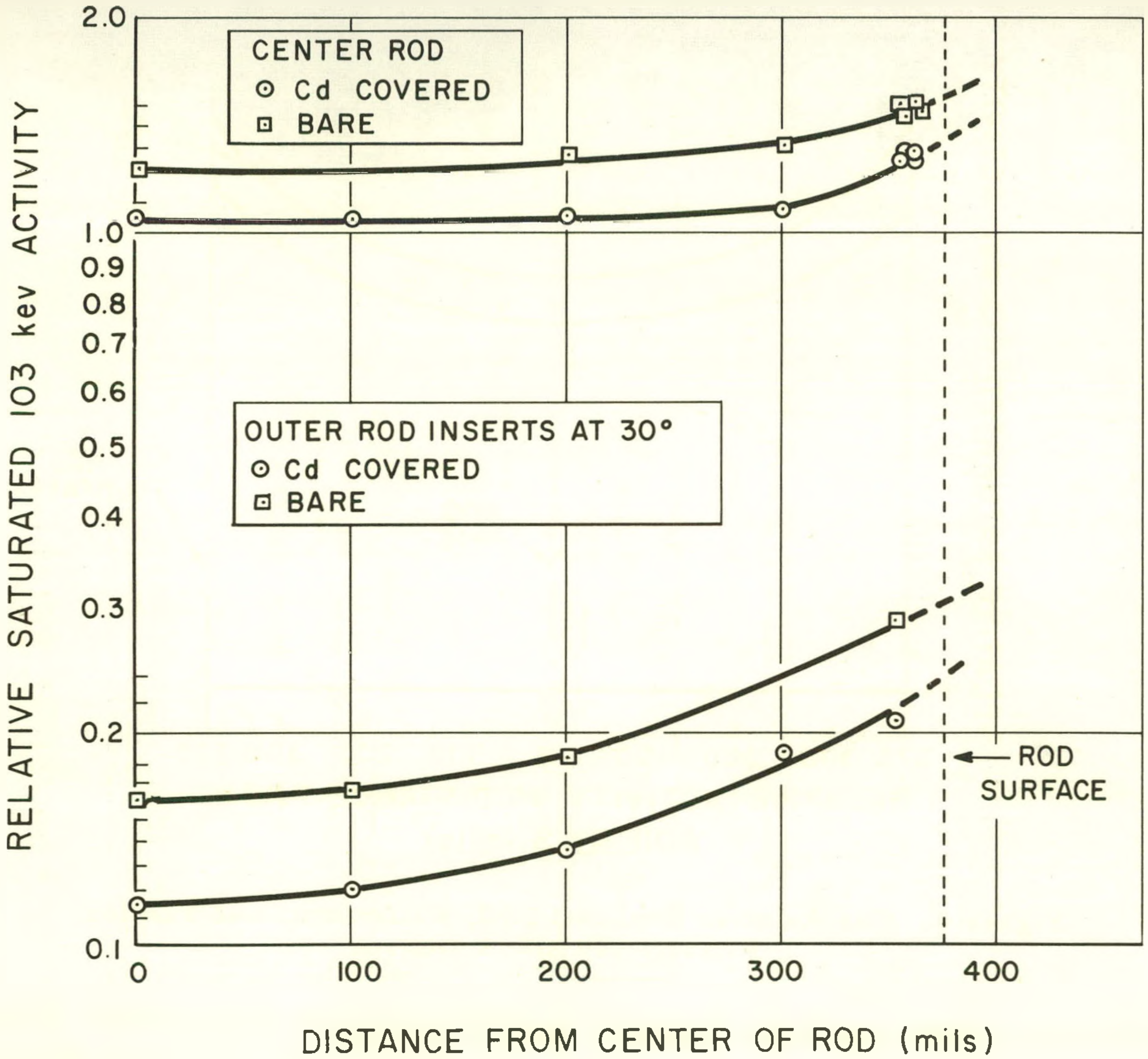

Figure 7. An Example to Show Extrapolation of Activities to Edge of Rod

To measure A_f, a pair of bare foils, one of natural uranium and the other a depleted foil, were irradiated in the center rods of two of the elements shown in Figure 5. These were then counted with the scintillation spectrometer in the same way as the depleted foils. The activities for the depleted and natural foils corrected to a common mass are given by

$$A_D = A_{49} + A_f$$

$$A_N = A_{49} + A_{Nf}$$

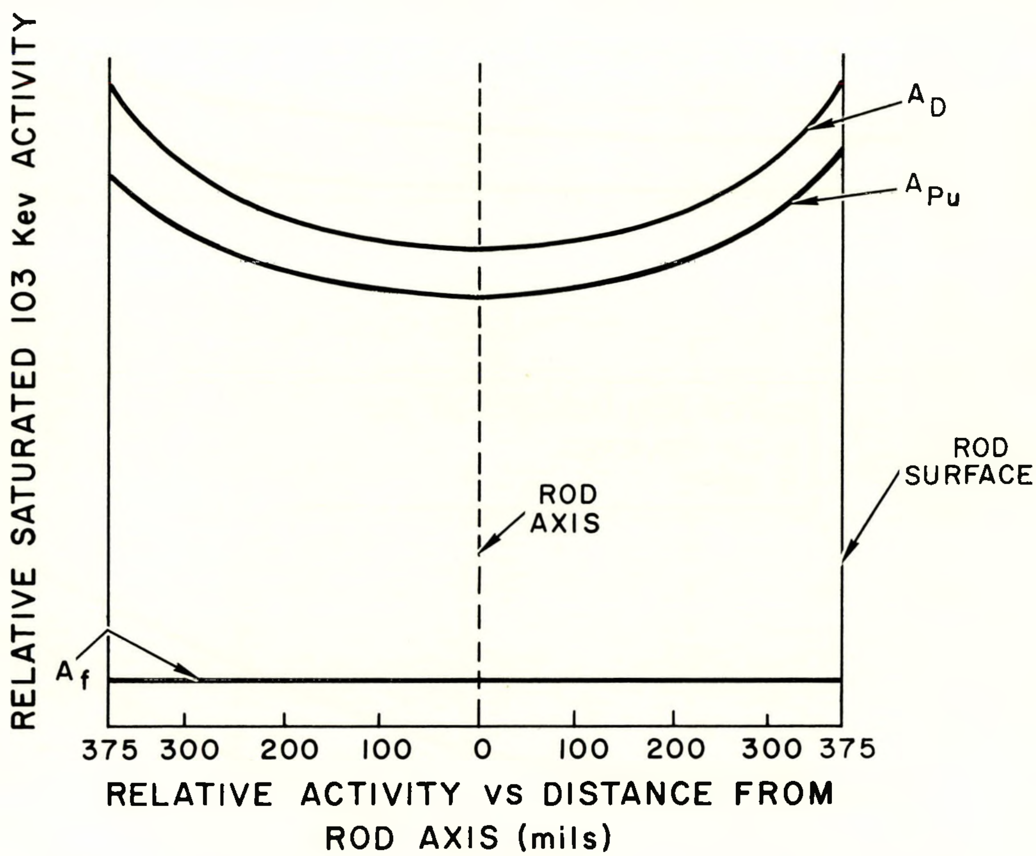

Figure 8. The Relative Depleted Foil, Plutonium, and Fission Product 103 kev Activities

where A_{Nf} is the fission product activity generated in the natural foil. The foils were then counted using an integral bias to accept gamma ray pulses greater than 0.5 mev. These activities, A_{Di} and A_{Ni}, are attributable mostly to the fission products. It was assumed that the measured ratio

$$r = \frac{A_{Di}}{A_{Ni}} ,$$

for pulses above 0.5 mev, was the same as the ratio of the counts due to attenuated fission gamma rays that produce counts in the 103 kev settings. This enables one to find the activity A_{49} of the depleted foils using the expression

$$A_{49} = \frac{A_D - rA_N}{1 - r} .$$

Finally, we have

$$A_f = A_D - A_{49} .$$

A_f is assumed to be constant over the lattice and is applied as a constant correction to all of the depleted foil activities to obtain the plutonium activities. The application of this correction changes ρ by about 0.3 % as shown by the value ρ_1 in the table. This corresponds to a change of only about 0.06 of a percent in the resonance escape probability and is negligible in this case.

With this value of p and the equation*

$$p = exp\left[- \frac{N_u V_u \sigma_1^{res}}{V_m (\overline{\xi\Sigma_s})_{graphite}} \right],$$

a value of the effective resonance integral, σ_1^{res}, for U^{238} with 1/v capture present can be obtained. The 1/v portion of this can be evaluated from

$$\sigma_{1/v}^{res} = \int_{0.487}^{\infty} 2.75 \sqrt{\frac{0.0253}{E}} \frac{dE}{E} .$$

The integral extends from the cadmium cutoff. If this cross section is subtracted, then a value of σ_{res}^{eff} corrected for 1/v capture is obtained. If this is used with the equation

$$p_2 = exp\left[- \frac{V_u N_u \sigma_{res}^{eff}}{V_m (\overline{\xi\Sigma_s})_{graphite}} \right],$$

* In the equation, N_u is the number of U^{238} atoms/cm^3; V_u is a volume of the fuel having a unit height and a cross sectional area of the fuel in an element; and $V_m = \sum V_i (\xi\Sigma_s) / (\xi\Sigma_s)_{graphite}$, where V_i is the volume fraction of the i^{th} material and the summation is to extend over the unit cell.

then a value of p_2 corrected for both fission product activity and 1/v capture can be obtained. The values of p_2, $\sigma^{res}_{1/v}$, σ^{res}_1, and σ^{eff}_{res} are shown in the table.

SUMMARY OF EXPERIMENTAL RESULTS

$\rho. = 2.66 \pm 0.02$	$\sigma^{res}_1 = 9.12 \pm 0.26$ barns
$p = 0.782 \pm 0.005$	$\sigma^{res}_{1/v} = 1.26$ barns
$\rho_1 = 2.65 \pm 0.02$	$\sigma^{eff}_{res} = 7.86 \pm 0.26$ barns

$$p_2 = 0.809 \pm 0.005$$

If the effective resonance integral for the element is of the form

$$\sigma^{res} = a + b\sqrt{S/M}$$

and if Hellstrand's[5] value of $b = 24.7$ is used, a value of 1.81 barns is obtained for a.

IV. COMPARISON WITH OTHER RESULTS

By analyzing a set of uranium-graphite exponential experiments with the aid of age-diffusion theory, in which the fuel element spacing was varied, F. L. Fillmore[4] has calculated values for the effective resonance integral and the resonance escape probability of the lattice for which p has been measured in the present work. These values were 7.7 barns and 0.813, respectively, and are thus in agreement with the present experimental determination.

Several laboratories[5,6,7,8,9] have measured the effective resonance integral for U^{238} as a function of surface-to-mass ratio of the fuel. M. V. Davis[10] has summarized and attempted to correlate these measurements. His results are shown in Figure 9. The straight lines on the graph represent the least squares best fit curves for the work done by Hellstrand, Davis, and Egiazarov. The value of the resonance integral for the appropriate $\sqrt{S/M}$ for the fuel elements used in this experiment is shown on the graph for comparison. The surface value for the element was that which would be taken up by a rubber band wrapped around the bundle of fuel rods. The results of the present work are not in disagreement with this empirical expression for the effective resonance integral.

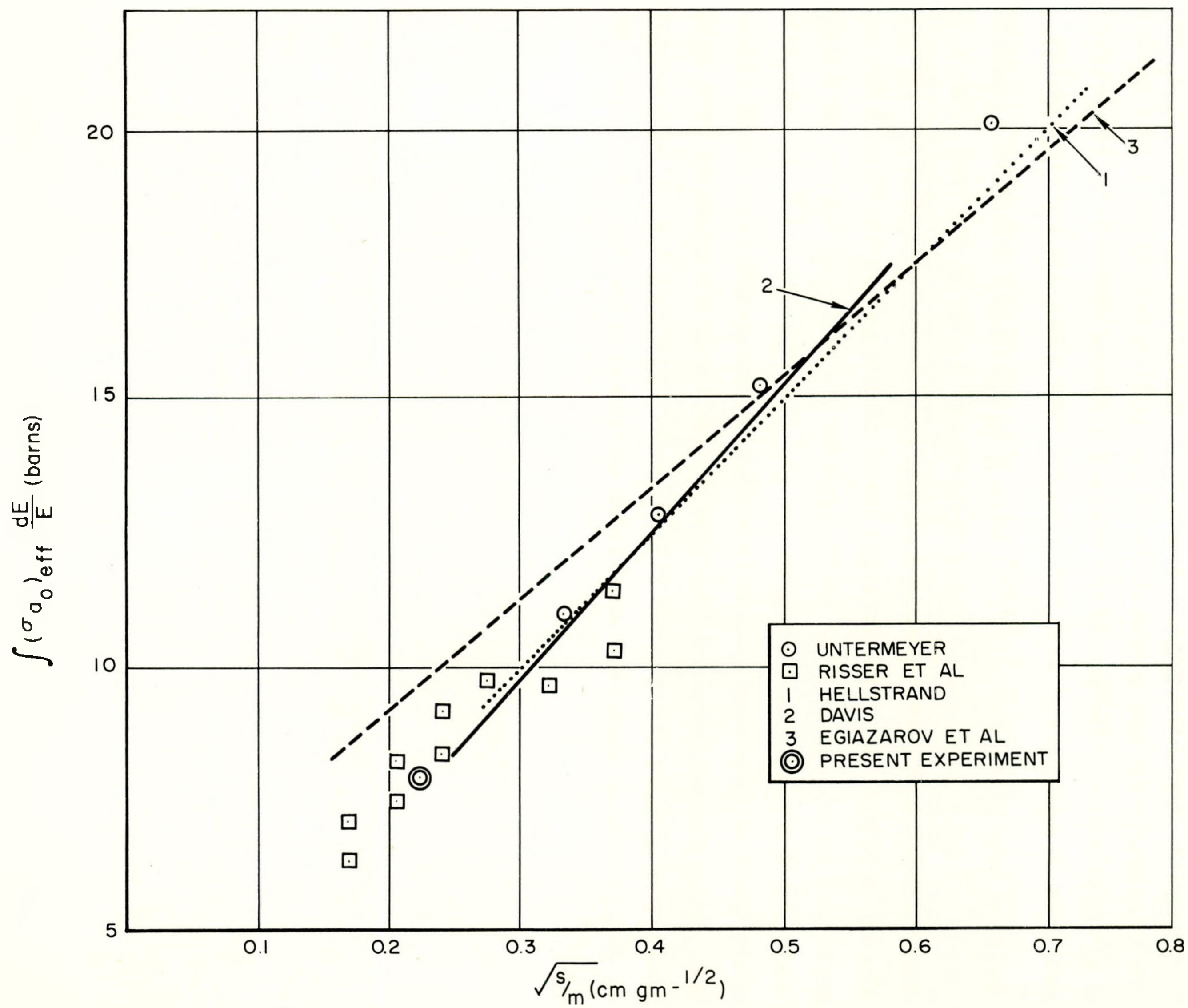

Figure 9. Values of the Effective Resonance Integral of U^{238} as a Function of $\sqrt{S/M}$

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