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PCTR MEASUREMENT OF k_{∞} FOR A TUBULAR
FUEL ELEMENT WITH INTEGRAL TARGET
IN A WATER LATTICE

C. L. Bennett and D. R. Oden

June 1970

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ABSTRACT

A measurement of the infinite medium neutron multiplication factor has been made for a tubular fuel containing an integral target rod in a light water lattice using the Physical Constants Test Reactor (PCTR). The concentration of boron in the moderator required to poison the cell to a k_{∞} of unity was determined from a null reactivity measurement. The multiplication constant and neutron utilization ratios have been inferred from measurements of the spatial distributions of neutron reaction rates, coupled with reactivity measurements. Considerable emphasis has been placed on the various techniques used to make corrections to foil activation-data.

In addition to the descriptions of the experiment and results, this report includes comparisons between experiment and theory. The comparisons between the angular-dependent radial activation distributions measured in the outer moderator for both the unpoisoned and the poisoned lattice and the distributions calculated using integral transport theory which utilized the standard "white" equivalent cylindrical cell boundary assumption should be of particular interest to those involved in the evaluation of theoretical methods.

The results of this experiment, coupled with previous critical approach and exponential experiments for this lattice, provide a benchmark problem for use in theoretical development and evaluation studies.

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1. INTRODUCTION

A measurement of the infinite medium neutron multiplication factor, k_{∞} , has been made for a tubular fuel element with integral target in a light water lattice using the Physical Constants Test Reactor (PCTR). The concentration of boron in the moderator required to poison the cell to a k_{∞} of unity was also determined from these measurements in the PCTR Water Tank.

Considerable emphasis in this report is placed on the various data correction techniques used. Included in the report are the development of some new approximate methods to obtain some of these corrections, descriptions of the standard correction methods and also sufficient tabulations of the corrections themselves to impart some intuition as to their relative magnitudes and, therefore, their importance (or lack thereof) to the final results.

Comparisons between experiment and one-and-two dimensional transport theory results are included in this report, in addition to a description of the experiments and results. Since angular dependent radial activation distributions were measured in the outer moderator for both the unpoisoned and poisoned lattice, the effect of assuming an isotropically reflecting, equivalent cylindrical, cell boundary in the theoretical model could be evaluated by a direct comparison with experiment. This comparison should be of particular interest to those involved in the evaluation of theoretical methods.

The results of this experiment, coupled with previous critical approach and exponential experiments, for this lattice,⁽¹⁾ provide a benchmark problem for use in theoretical development and evaluation studies.

2. SUMMARY

Experimental values for the infinite medium neutron multiplication factor, k_{∞} , and the concentration of boron in the water moderator required to poison the unit lattice cell to a k_{∞} of unity have been determined for a 3.1 in. triangular pitch lattice of tubular fuel with integral targets. Results of these measurements, conducted in the Physical Constants Test Reactor (PCTR), for the 2.1 wt% ^{235}U metal tubes with lithia-aluminate targets, are summarized below together with the results of calculations.

<u>Nominal Condition</u>	<u>wppm Boron</u>	<u>k_{∞}</u>		
		<u>Poisoned Technique</u>	<u>ID Transport Theory</u>	<u>2D Transport Theory</u>
Unpoisoned	0	1.1063 ± 0.0084	1.0926	1.094 ± 0.003
At Measured Null Reactivity Boron Concentration	550 ± 12	1.0	0.995	0.996 ± 0.002

The above value of the unpoisoned k_{∞} inferred from measurement very likely includes a positive systematic error due to the end effect, which is estimated to be on the order of 4 mk. Based on this best estimate, the authors recommended the corrected values of the unpoisoned k_{∞} of 1.1019 ± 0.0087 and the critical boron concentration of 528 ± 12 wppm for this lattice.

The overall excellent theory-experiment correlations obtained supports both the accuracy of the experimental results and the adequacy of the methods in spite of some of the difficulties encountered in the analysis of this experiment.

3. DESCRIPTION OF THE EXPERIMENT

This section describes the experimental arrangement of the test lattice in the PCTR Water Tank and the geometry of the test lattice fuel. The water tank is inserted in the large central test cavity of the PCTR in order to perform these experiments in the graphite moderated PCTR.

3.1 Test Lattice in PCTR Water Tank

The PCTR Water Tank is a cylindrical vessel, 17.5 inches inside diameter and ~37 inches long. An aluminum drip pan beneath the tank centers it in the PCTR test cavity which is 41.25 x 41.25 x 37.5 inches.

Six-1/4 inch thick plexiglass templates supplied structural support for the 19 element lattice of tubular fuel elements inside the tank. These templates also supported 12 columns of 0.95 wt% ²³⁵U uranium metal fuel located between the 19 element array and the tank edge, which provided for adjustment of the neutron spectrum incident on the test lattice.

The removable center cell section was 24 inches long, hexagonal in cross section and contained one fuel element. The element and associated moderator were contained in a box with 1/16 inch thick plexiglass sides and 1/2 inch thick aluminum ends. The inside distance between opposite sides of the hexagon was 3.1 inches, representing a unit cell.

End buffers for the center cell were 6 inches long. The center cell and end buffers were contained in a zirconium can (0.020 in. wall thickness) which extended the full length of the tank so that the cell and buffers could be loaded and unloaded without having to drain and fill the tank. The first radial buffer ring (6 elements) extended the full length of the tank. The second ring (12 elements) extended over only the central 26.5 inches of the 37 inch length, due to the limited amount of fuel available. Aluminum spacers were used to center this buffer ring axially and also to displace the excess moderator.

The various components used in making up the removable central cell and end buffer assemblies are shown in Figure 1. Loading of the test lattice front buffer into the water tank is shown in Figure 2. A simple schematic depicting the 19 element test array surrounded by the additional 12 columns of 0.95 wt% enriched uranium radial buffer fuel is shown in Figure 3. Figure 4 shows the removable central cell being loaded into the PCTR water tank.

FIGURE 1. CENTRAL TEST CELL COMPONENTS

FIGURE 2. TEST LATTICE BUFFER LOADING IN PCTR WATER TANK

FIGURE 3. PCTR WATER TANK TEST LATTICE LOADING

FIGURE 4. CENTRAL CELL LOADING IN PCTR WATER TANK

3.2 Lattice Geometry

The rod-in-tube assembly consisted of an annular fuel region of uranium enriched to 2.1 wt% ^{235}U and a $\text{Li}_2\text{O}(\text{Al}_2\text{O}_3)_{1.155}$ target rod having 3.14 wt% ^6Li in Li, 9.45 wt% Li in $\text{Li}_2\text{O}(\text{Al}_2\text{O}_3)_{1.155}$ with the $\text{Li}_2\text{O}(\text{Al}_2\text{O}_3)_{1.155}$ at 74% of theoretical (2.62 gm/cm^3) density.⁽²⁾ The uranium is clad in zirconium and the target in aluminum and zirconium. Further details of the composition and geometry of the unit cell are given in Table I. An isotopic analysis of the test fuel is given in Table II. Each end cap detail is shown in Table III.

TABLE I
COMPOSITION AND GEOMETRY OF THE UNIT CELL*

<u>Region</u>		<u>Isotope</u>	<u>Radii</u>	<u>Density</u>
<u>Name</u>	<u>No.</u>		<u>(Outside)</u> <u>Cm.</u>	<u>g/cc</u>
Target	1		1.366	1.9388
		${}^6\text{Li}$		0.00575
		${}^7\text{Li}$		0.1775
		Al		0.8155
		O		0.938
Clad	2	Al	1.620	2.720
Clad	3	Zr	1.695	6.40
Water	4	H_2O	2.182	1.000
Clad	5	Zr	2.247	6.400
Fuel	6	U	2.960	18.82
		${}^{235}\text{U}$		0.3894
		${}^{238}\text{U}$		18.43
Clad	7	Zr	3.045	6.400
Water	8	H_2O	4.134 ^(a)	1.000

*Fuel and Target information is from Reference 3

(a)Cylindricized Radii

TABLE II

MASS SPECTROMETER ISOTOPIC ANALYSIS OF TEST CELL FUEL*

<u>Isotope</u>	<u>Sample No. 1</u>	<u>Sample No. 2</u>
	<u>Weight %</u>	<u>Weight %</u>
^{238}U	97.878 $\pm$ 0.010	97.873 $\pm$ 0.010
^{236}U	0.0215 $\pm$ 0.0004	0.0219 $\pm$ 0.0004
^{235}U	2.091 $\pm$ 0.010	2.096 $\pm$ 0.010
^{234}U	0.0087 $\pm$ 0.0003	0.0088 $\pm$ 0.0003

* Quoted uncertainties are for 95% confidence intervals

TABLE III

END CAP DETAIL (a)

<u>Target (b)</u>				
<u>Material</u>	<u>Diameter</u> <u>cm</u>	<u>Thickness</u> <u>cm</u>	<u>Mass per</u> <u>cap/g</u>	<u>Number in</u> <u>Central Cell</u>
Al	2.837	0.576	9.87	4 ^(c)
Zr	3.233	0.462	24.28	2 ^(c,e)
<u>Fuel (d)</u>				
Zr	ID = 6.884 OD = 8.270	0.249	137	2 ^(e)

- (a) The total target length includes 22.508 inches of target material, 1.271 inches of end caps and a 0.221 inch air gap.
- (b) Target end cap masses do not include the cladding.
- (c) The target was two separate aluminum clad pieces that were in turn clad in zirconium.
- (d) Fuel end cap masses do include the cladding.
- (e) The measured value of k_{∞} was for a fuel element without the zirconium end caps.

4. EXPERIMENTAL ANALYSIS TECHNIQUES AND RESULTS

This section of the report describes the experimental and analysis techniques used in this experiment and presents the primary results obtained therefrom. The null reactivity technique of determining k_{∞} is first briefly outlined followed by a description of the determination of the spectral equilibrium in the test lattice. Next, the reactivity measurements and their relationships to the just critical boron content is described followed by a discussion and results of the calibration method used to determine the boron concentration in the water. The next subsection entitled "Relative Reaction Rate Measurements" outlines the extent of the copper activation measurements, presents the results, and describes in detail the combined measurement/calculational methods of obtaining the axial, radial, and cell-averaged copper activation rate distributions in the various material regions of the test lattice. The cross sections used in the analysis and the codes from which they were obtained are listed next. The latter part of this section includes the determination of the ^{63}Cu $1/v$ absorption rates, the $1/v$ utilizations, and k_{∞} .

4.1 The PCTR Null Reactivity Technique for Determining k_{∞}

The technique and experimental procedure for determining the infinite medium neutron multiplication factor (k_{∞}) utilizing the Physical Constants Test Reactor (PCTR) is described elsewhere.^(4,5) Only a brief outline of the method as it applies to measurements made in the PCTR water tank will be presented here.

The measurement of k_{∞} by the null reactivity technique requires the following:

1. The neutron energy distribution in the test cell must be typical of that found in an infinite array of cells. This is accomplished by surrounding the test cell with "buffer" cells of the same composition as the test cell. In addition, adjacent to the cavity containing the water tank is a natural uranium-graphite "spectral buffer zone" which is surrounded by a graphite ^{235}U driver zone and a graphite reflector. Spectral equilibrium is established by adjusting the natural uranium-graphite composition until measured integral spectral index values in the test cell agree with those of the adjacent buffer cells.
2. The mass of neutron absorber (boron) required to reduce the multiplication of the test section to unity (under the proper neutron energy spectral conditions indicated above) must be accurately measured and is determined by achieving a null difference in the PCTR excess reactivity with the poisoned cell in and out of the reactor.
3. The relative reaction rates in the test cell components are measured under conditions of spectral equilibrium in both the unpoisoned cell and the cell poisoned to unit multiplication. The spatial distribution of the neutron reaction rates in each region of the test cell are required for the determination of the $1/v$ utilization for the unpoisoned test cell and for the cell poisoned with the correct mass of absorber. The ratio of these utilizations yields the multiplication constant.

4.2 Determination of Spectral Equilibrium in the Test Lattice

The integral spectral index used to determine if spectral equilibrium between the test cell and the adjacent buffer cells had been achieved was a measured gold cadmium ratio. Bare and cadmium covered gold pins, 0.020 in. dia. x .25 in. long, were placed on the fuel clad surface throughout the test cell and buffer regions at equivalent positions to obtain these data.

The radial traverse data shown in Figure 5 indicate that spectral equilibrium was achieved between the center cell and first radial buffer ring within the accuracy of the measured cadmium ratios ($\pm 1\%$) for both the unpoisoned and poisoned (566 wppm boron) cases. In the latter case, borated polyethylene sheets were used in the radial and axial buffer regions to bring the spectrum into equilibrium. The amount of material required in the radial buffer for a given boron concentration in the center cell was determined by reactivity measurements. The worth of borated polyethylene on the cell boundaries relative to the worth of boric acid in the center cell was used to find the thickness of borated polyethylene at the cell boundary equivalent to a given concentration of boron in the center cell.

FIGURE 5. RADIAL VARIATION OF GOLD CADMIUM RATIO

Cadmium ratio measurements were not made beyond the first radial buffer region for the poisoned case since the localized poison would give false spectral index values for pins on the fuel clad surface near the poison.

The axial traverse data shown in Figure 6 illustrate the thermal flux peaking at the fuel clad surface in the axial center of the cell due to the presence of the aluminum "mid caps" in the center of the target. The peaks at the center cell/end buffer interface are due to thermal flux peaking caused by the aluminum end plates on the center cell and end buffer containers.

Corrections to the reaction rates in each region resulting from these effects amounted to only a few per cent in all cases and the affect on the measured value of $k_{\infty}-1$ was essentially negligible. Corrections to the reaction rates in the cell components for flux peaking caused by the "midcaps" and end caps are discussed in a later section (Relative Reaction Rate Measurements) which includes the axial copper traverse data actually used to make all the aforementioned corrections.

4.3 Reactivity Measurements

The concentration of boron in the moderator required to absorb the excess neutrons produced in the test cell is determined by the null reactivity technique. The basis for this measurement is that when the proper concentration of poison is attained the test cell will have the same neutron multiplication properties as a void, i.e., a k_{∞} of unity. There will then be no reactivity change upon removing the properly poisoned cell.

FIGURE 6. AXIAL VARIATION OF GOLD CADMIUM RATIO

The actual measurements which are carried out in applying the technique consist of determining the PCTR excess reactivity by period measurement. Measured reactivities are corrected for temperature and pressure changes during the measurements using measured coefficients. Reactivities are measured for the following conditions:

1. Cell In(CI) - the reactivity of the reactor with the test cell in and containing a concentration(B) of boron in the moderator.
2. Cell Out (CO) - the reactivity of the reactor with the test cell removed from the reactor.
3. Cell Out Standard Absorber (COSA) - the reactivity of the reactor with the test cell removed and a standard absorber (copper) in the void.
4. Cell in Δ Poison (CI Δ B)-the reactivity of the reactor with the test cell in and containing a concentration of boron, $B + \Delta B$, in the moderator.

The worth of the cell relative to a void is then given by $\Delta\rho_{\text{cell}} = \text{CI} - \text{CO} - \Delta\rho_N$ where $\Delta\rho_N$ is a small correction to account for the presence of nitrogen in the air atmosphere which replaces the cell in the CO condition. As is shown in Section 5.1, $\Delta\rho_N$ is proportional to the worth of copper in the cell out case, i.e., $\Delta\rho_N \sim \Delta\rho_{\text{Cu}}^{\text{cavity}} = \text{CO} - \text{COSA}$.

For a given concentration (B) of boron in the cell for the CI case, the incremental concentration, ΔB_o , required to poison the cell to a multiplication of unity is given by

$$\Delta B_o = \Delta\rho_{\text{cell}} / (\Delta\rho_{\Delta B} / \Delta B),$$

where $\Delta\rho_{\Delta B}/\Delta B$ is the sensitivity of the cell worth at a boron concentration, B , to a small change, ΔB , in this concentration. The quantity $\Delta\rho_{\Delta B}$ is given by

$$\Delta\rho_{\Delta B} = CI - CISA.$$

The null reactivity concentration (B_0) is then

$$B_0 = B + \Delta B_0.$$

Although it is not practical to obtain a system for which $B \equiv B_0$ ($\Delta\rho_{\text{cell}}$ precisely zero), the determinations of B_0 should be made from both over-poisoned ($B > B_0$) and under-poisoned ($B < B_0$) cases for which B is close to B_0 since for large values of B , $\Delta\rho_{\Delta B}$ is nonlinear with B .

In the present experiment, the null reactivity boron concentration of 550 ± 12 wppm was obtained by linear interpolation from reactivity measurements made at 549 ± 4 and 566 ± 3 wppm boron in the moderator followed by a small correction ($\sim 1\%$) for the effect of the .020 inch thick zirconium container surrounding the test cell. This correction was obtained as follows:

1. Reactivity measurements were made with the above boron concentrations both with and without .010 inch thick zirconium shims on the zirconium container.
2. For both conditions, the cell worth, normalized to the worth of copper in the cavity, was plotted as a function of boron concentration in the moderator.*

* The normalized cell worth provides a more linear variation with boron concentration than does the cell worth alone since changing spectral conditions, which produce a nonlinearity in cell worth as a function of boron concentration, tend to cancel in the normalization. The small nonlinearities caused by self-shielding changes are still present however.

3. Null reactivity boron concentrations were interpolated for both conditions, yielding 557 ± 4 and 561 ± 4 wppm boron for the absence and presence of shims, respectively.
4. These null reactivity boron concentrations were then plotted as a function of zirconium thickness. Linear extrapolation to zero zirconium thickness yielded $B_o = 550 \pm 12$ wppm boron.

4.4 Determination of Boron Concentration in Water

Since the infinite medium excess neutron multiplication, $k_{\infty}-1$, is directly proportional to the poison concentration, a precise determination of the latter is necessary for precise measurements of $k_{\infty}-1$. To obtain a given boron concentration in solution the desired amount of boric acid crystals are weighed out and combined with an accurately determined volume of distilled water. The weight and volume determinations introduce only about a 0.1% error in the boron concentration. However, boric acid crystals are hygroscopic and the weight of the crystals, and hence the boron content, will depend on the amount of moisture contained in the crystals which will vary from sample to sample.

In order to determine the boron content of a solution with these unknown combined uncertainties, a calibration curve has been obtained from a series of reactivity measurements in the Thermal Test Reactor (TTR). Reactivity worths of 14 samples of different nominal boron concentrations, supplied by Chemical Standards - BNW, were measured relative to a pure distilled water sample. A sample size of 50 cm³ solution contained in thin walled aluminum cans was found to allow measurements over a concentration range of 0 to 2000 wppm (weight parts per million) without the necessity of control rod calibrations.

Measurements on the samples of a given nominal boron concentration were alternated with the water standard. A correction for reactor drift was obtained from a linear least squares fit of the water standard reactivity as a function of time during each half-day series of runs. The boron worth of a given sample was then the difference between the worth of the boron containing sample and that of the water standard

corrected to the time of measurement of the sample. The results of individual determinations were then used to get an average boron worth at a given concentration and the uncertainty in this worth was found using standard statistical techniques.

A calibration curve was made by least squares fitting the function $x = ay + by^2$ to the data, using the multidimensional least-squares program LIKELY.⁽⁶⁾ Using the average values of boron worths and uncertainties calculated therefrom, and nominal boron concentrations, percentage errors in boron concentrations were uniformly adjusted until the χ^2 of the fit agreed with the number of degrees of freedom associated with the problem. Thus, assuming the uncertainties in reactivities to be known exactly, the above condition was met for an uncertainty in boron concentration of approximately 1%.

The best fit parameters for the function $x = ay + by^2$ were found to be:

$$\begin{aligned} a &= 83.81 & \sigma_a^2 &= 0.4887 \\ b &= 0.8410 & \sigma_b^2 &= 0.00333 \\ & & \sigma_{ab} &= -0.03552 \end{aligned}$$

where, x = wppm boron in sample;

y = reactivity worth of boron in cents.

The uncertainty in a boron concentration obtained using the calibration curve is, by propogation of errors,

$$\sigma_x = \sqrt{y^2 \sigma_a^2 + (a + 2by)^2 \sigma_y^2 + y^4 \sigma_b^2 + 2y^3 \sigma_{ab}}$$

where y and σ_y^2 are determined from TTR reactivity measurements and the other quantities are as given above.

4.5 Relative Reaction Rate Measurements

Relative reaction rates in ^{63}Cu in the test cell components are determined from foil activation measurements performed in both the poisoned and unpoisoned lattices after spectral equilibrium had been achieved. Bare and cadmium covered copper foils are activated in the cell in separate irradiations with normalization between irradiations being provided by bare monitor foils activated in an external thermal column.⁽⁷⁾

Several sets of foil traverses were made in this experiment. Bare circular 0.010 inch thick copper foils of the same diameter as the target were used to obtain an axial traverse of the average activation rate in the target. This axial traverse yielded an axially averaged activation rate as well as information on the flux peaking effects in the target resulting from the target midcaps and end caps. In order to obtain properly averaged activation rates in other regions, 30° copper sector foils, 0.010 inch thick, were irradiated bare in the inner moderator, fuel, and outer moderator regions.

Bare and cadmium covered 0.036 inch diameter copper pins were activated on the fuel cladding surface at various axial positions to provide additional information on axial flux peaking effects of mid-caps and end caps. Pins of this type were also used in a special plexi-glass holder to obtain radial traverses in the outer moderator region. In the target region, 0.062 inch diameter copper pins provided additional activation data.

Bare and cadmium covered foils were also irradiated at various positions throughout the cell to provide additional normalization and activation data. Axially averaged activation rates in all cell components were obtained by fitting the measured point and integral data to one and two-dimensional transport theory calculations. Corrections to the reaction rates in each region resulting from axial end effects were established by determining the average reaction rate axially relative to that at a specific radial position. Corrections for these effects were generally on the order of a few percent.

Standard foil counting techniques were employed utilizing a NaI detector system biased to accept only pulses representing gamma energies in excess of 400 kev. The specific activation of a foil relative to a similar foil in the thermal column was calculated using a revised version of the computer code APDAC-I,⁽⁸⁾ which corrects the counting data for activity decay during counting, room background, foil mass differences, residual activity, and detector system dead time losses. Further corrections to the experimental data required to yield the final $1/v$ activation rates are discussed in section 5.

4.5.1 Axial Copper Activation Rate Distribution

The PCTR leveling rings lacked sufficient source strength to flatten out the axial flux variation across the removable center cell in this water lattice experiment. This variation was due primarily to the fact that sufficient test assemblies to fill out the front and back of the second buffer ring were unavailable, making the major portion of the whole test lattice somewhat egg shaped. The resulting gross axial variation in

the activities of the bare and cadmium covered copper detectors complicated the data analysis considerably as compared to the usual PCTR experiment.

The 1.076 inch diam. by 0.010 inch thick copper target foil data are summarized in Table IV for both the unpoisoned and poisoned lattices. The axial variation of the subcadmium and cadmium covered copper activities is shown in Figures 7 and 8. The cadmium covered activities are labeled "inferred" due to the fact that they were obtained indirectly from measurements in other regions, as discussed in a latter section. The 0.036 inch diam. by 0.25 inch long copper pin axial data obtained on the outer fuel clad surface are tabulated in Table V for both lattices. The axial variation of the subcadmium and cadmium covered pin activities can be seen in Figure 9.

The portion of the measured target region axial traverse unperturbed by the aluminum mid- and end-caps was fit to a cosine shape $f(z)$ using the program LEARN⁽⁹⁾ with the following results:

Unpoisoned Lattice

$$f(z) = \text{Cos} \left[2.289 \times 10^{-2} \text{ cm}^{-1} (z - 0.9439 \text{ cm}) \right]$$

Poisoned Lattice

$$f(z) = \text{Cos} \left[2.078 \times 10^{-2} \text{ cm}^{-1} (z - 0.9346 \text{ cm}) \right]$$

TABLE IV

Target Region Axial Copper Foil Activation DataA. Unpoisoned Lattice

<u>Z (cm)</u>	<u>SA_B⁶³</u>	<u>SA_{Cd}^{63*}</u>	<u>SA_{Sub Cd}⁶³</u>	<u>SA_{1/v}⁶³</u>
-29.9085	2.39121	0.41553	1.97568	2.19308
-29.2938	2.06582	0.41649	1.64933	1.86723
-21.0998	1.57878	0.45931	1.11947	1.35978
-8.8087	1.77137	0.51170	1.25967	1.52739
-0.6147	2.30539	0.54068	1.76471	2.04759
0.0	2.50315	0.54667	1.95648	2.24249
0.6147	2.32417	0.54101	1.78316	2.06621
8.8087	1.76532	0.51693	1.24839	1.51884
17.0028	1.69441	0.48697	1.20744	1.46222
25.1968	1.53513	0.45068	1.08445	1.32024
29.2938	2.09595	0.43102	1.66493	1.89044
29.9085	2.43886	0.43042	2.00844	2.23363

B. Poisoned Lattice

<u>Z (cm)</u>	<u>SA_B⁶³</u>	<u>SA_{Cd}^{63*}</u>	<u>SA_{Sub Cd}⁶³</u>	<u>SA_{1/v}⁶³</u>
-29.2938	1.30960	0.27138	1.03822	1.18020
-25.1968	0.90053	0.28147	0.61906	0.76632
-21.0998	0.95243	0.29176	0.66067	0.81332
-17.0028	0.98000	0.30127	0.67873	0.83635
-12.9057	1.01772	0.31019	0.70753	0.86981
-8.8087	1.04796	0.31862	0.72934	0.89604
-4.7117	1.05058	0.32650	0.72408	0.89490
-0.6147	1.32490	0.33520	0.98970	1.16507
0.0	1.43454	0.33818	1.09636	1.27329
0.6147	1.31891	0.33536	0.98355	1.15901
4.7117	1.08191	0.32774	0.75417	0.92564
8.8087	1.03782	0.32091	0.71691	0.88481
12.9057	1.01800	0.31351	0.70449	0.86852
17.0028	1.01115	0.30562	0.70553	0.86543
21.0998	0.96386	0.29713	0.66673	0.82219
25.1968	0.93344	0.28785	0.64559	0.79619
29.2938	1.33983	0.27880	1.06103	1.20690

*Inferred

FIGURE 7. AXIAL COPPER FOIL TRAVERSES IN THE TARGET REGION OF THE UNPOISONED LATTICE

FIGURE 8. AXIAL COPPER FOIL TRAVERSES IN THE TARGET REGION OF THE POISONED LATTICE

TABLE V

Outer Fuel Clad Surface^a Copper Pin ActivitiesA. Unpoisoned Lattice

<u>Z (cm)</u>	<u>SA⁶³_{Sub Cd}</u>	<u>SA⁶³_{Cd}</u>	<u>SA⁶³_B</u>	<u>CdR⁶³</u>	<u>SA⁶³_{1/v}</u>
-29.6037	2.65252	0.42251 ^b	3.07503	7.2780	2.88684
-25.40	2.76375	0.46116	3.22491	6.9930	3.01951
-20.32	2.87644	0.51456	3.39100	6.5901	3.16181
-15.24	2.97044	0.52549	3.49593	6.6527	3.26188
-10.16	3.05436	0.54982	3.60418	6.5552	3.35929
- 5.08	3.18873	0.56356	3.75229	6.6582	3.50128
0.0	3.28546	0.56488	3.85034	6.8162	3.59874
5.08	3.16628	0.55830	3.72458	6.6713	3.47591
10.16	3.06970	0.54065	3.61035	6.6778	3.36954
15.24	3.05420	0.52546	3.57966	6.8124	3.34562
20.32	2.91926	0.50402	3.42328	6.7920	3.19879
25.40	2.74802	0.47362	3.22164	6.8022	3.01069
29.6037	2.68342	0.43747	3.12089	7.1340	2.92604

B. Poisoned Lattice

<u>Z (cm)</u>	<u>SA⁶³_{Sub Cd}</u>	<u>SA⁶³_{Cd}</u>	<u>SA⁶³_B</u>	<u>CdR⁶³</u>	<u>SA⁶³_{1/v}</u>
-29.60	1.47428	0.27492	1.74920	6.3626	1.62675
-25.40	1.41358	0.29111	1.70469	5.8558	1.57503
-20.32	1.48892	0.31266	1.80158	5.7621	1.66232
-15.24	1.60145	0.32563	1.92708	5.9180	1.78204
-10.16	1.63385	0.33698	1.97083	5.8485	1.82074
- 5.08	1.65304	0.33848	1.99152	5.8837	1.84076
0.0	1.73704	0.34747	2.08451	5.9991	1.92975
5.08	1.69118	0.33977	2.03095	5.9774	1.87962
10.16	1.56554	0.33053	1.99607	6.0390	1.84885
15.24	1.5338	0.32335	1.85673	5.7422	1.71271
20.32	1.54711	0.31506	1.86217	5.9105	1.72184
25.40	1.45962	0.29646	1.75608	5.9235	1.62404
29.60	1.53599	0.28207	1.81806	6.4454	1.69243

a r = 3.0907 cm

b inferred

FIGURE 9. AXIAL COPPER PIN ACTIVATION TRAVERSES ON OUTER FUEL CLAD SURFACE

4.5.2 Radial Copper Activation Rate Distribution

The 0.010 inch thick copper foil activities at $Z = -9.6012$ cm. for the various material regions are summarized in Table VI. This axial position was chosen primarily because it was the actual position of both the inner and outer moderator sector foils and it was also reasonably close to the position of the target sectors. The axial perturbations caused by the aluminum end- and mid-caps in the target at this position are essentially negligible. Therefore, the data in Table VII provide a good representation of the typical relative copper activation rate distribution in the different radial regions and provide a basis for comparison with one-dimensional calculations.

The separable fuel element, utilized in the determination of the activation rate in the fuel itself, was initially designed for measurements in a graphite lattice.⁽³⁾ There were no provisions in the design of this element to allow cadmium covered activation rates in the fuel to be measured. Thus, as was done in the previous experiment,^(2,3) the epi-cadmium reaction rates in all regions were obtained by fitting radial and axial traverses calculated using transport theory to a few measured epi-cadmium data points.

The calculated epi-cadmium activation distribution (two dimensional transport theory results modified by the fitted axial cosine) was normalized (best fit) to the measured activities of three 0.313 in. diameter by 0.010 in. thick cadmium covered copper foils. Two of these foils were positioned 4 inches from the rear of the test cell ($Z = 19.7612$ cm)—one lying flat on the target clad surface and the other lying flat on the outer fuel clad surface.

TABLE VI

0.010 Inch Copper Foil Activities at $Z_o = -9.6012$ cmA. Unpoisoned Lattice

Region	SA_B^{63}	SA_{Cd}^{63}	$SA_{Sub\ Cd}^{63}$	$SA_{1/v}^{63}$
Target	1.76403	0.50867	1.25536 ^a	1.52149
Target Al Clad	2.08380	0.51677	1.56703	1.83740
Target Zr Clad	2.15437	0.51956	1.63481	1.90664
Inner Moderator	2.57736	0.52038	2.05698	2.32924
Fuel Inner Zr Clad	2.25210	0.51005	1.74205	2.00890
Fuel	2.36833	0.50371	1.86462	2.12816
Fuel Outer Zr Clad	2.94500	0.52569	2.41931	2.69435
Outer Moderator	5.19370	0.55232	4.64138	4.93035

B. Poisoned Lattice

Region	SA_B^{63}	SA_{Cd}^{63}	$SA_{Sub\ Cd}^{63}$	$SA_{1/v}^{63}$
Target	1.04224	0.31698	0.72526 ^a	0.89110
Target Al Clad	1.33535	0.32195	1.01340	1.18184
Target Zr Clad	1.37683	0.32377	1.05306	1.22245
Inner Moderator	1.46519	0.32404	1.14115	1.31068
Fuel Inner Zr Clad	1.36717	0.31757	1.04960	1.21575
Fuel	1.37769	0.31373	1.06396	1.22810
Fuel Outer Zr Clad	1.81230	0.32724	1.48506	1.65627
Outer Moderator	2.90362	0.34648	2.55714	2.73841

a. Average of sector and two round foils corrected to Z_o .

The third foil was 8 inches from the rear ($Z = 9.6012$ cm) and radially covered most of the outer moderator. The worst disagreement between the resulting normalized distribution and the measured data points was 1.3 and 2.0 percent, respectively, for the unpoisoned and poisoned lattices. All necessary epi-cadmium foil data were then determined from these fitted distributions and assigned the above errors. The effect of these errors on the final result (k_{∞}) is negligible within the quoted precision.

Bare copper sector foils (0.010 in. thick) were irradiated in the major cell regions at three different axial positions with respect to the center of the 23.56 inch long removable test cell. The uncorrected APDAC results for these foils are tabulated below:

Uncorrected Bare Sector Foil Data

Region	Z(cm)	$SA_{Bare}^{uc} \pm (\% \text{ Error})$	
		Unpoisoned	Poisoned
Target	-12.9057	1.79913 (0.364)	1.04953 (0.310)
Inner Moderator	- 9.6012	2.60695 (0.360)	1.47495 (0.332)
Fuel	0.0	2.66510 (0.340)	1.54270 (0.248)
Outer Moderator	- 9.6012	5.24234 (0.207)	2.92170 (0.175)

These sector foil data coupled with the fitted epi-cadmium results described above provide the basis for determining the following corrected sub-cadmium and cadmium covered ^{63}Cu activities in these regions.

Sub. Cd & Cd Covered 0.010 Inch Copper Sector Foil Activities

<u>Region</u>	<u>Z (cm)</u>	<u>SA⁶³_{Sub Cd}</u>	<u>SA⁶³_{Cd}</u>	<u>SA⁶³_{Sub Cd}</u>	<u>SA⁶³_{Cd}</u>
Target	-12.9057	1.24187	0.49583	0.71117	0.31019
Inner Moderator	- 9.6012	2.05698	0.52038	1.14115	0.32404
Fuel	0.0	2.02820	0.53147	1.15128	0.32928
Outer Moderator	- 9.6012	4.64138	0.55232	2.55714	0.34648

The target and fuel sector foil data were corrected to the axial position of the inner and outer moderator sector foils using copper activation distributions calculated with the DOT⁽¹³⁾ program.

$$SA(Z_o = -9.6012 \text{ cm}) = C_p(Z_o, Z) SA(Z).$$

The calculated axial position correction factors are tabulated below:

<u>Sector</u>	<u>C_p(Z_o, Z)</u>			
	<u>Unpoisoned</u>		<u>Poisoned</u>	
	<u>Sub Cd</u>	<u>Cd</u>	<u>Sub Cd</u>	<u>Cd</u>
Target	1.02633	1.02590	1.02231	1.02188
Fuel	0.91935	0.94782	0.92416	0.95278

Most of the Sub Cd and Cd fuel correction (about 70% and 50% of $|1-C_p|$) is due to the flux peaking in the fuel sector caused by the target mid-caps, while most of the target correction (about 83% of $|1-C_p|$) is due to the overall axial cosine shape since the target sector was fairly well isolated from the aluminum end- and mid-caps.

The calculated (ANISN)⁽¹²⁾ radial region averaged 0.010 in. copper activation rates for the target, inner moderator, fuel, and outer moderator regions were independently compared to the respective measured sub-cadmium foil data at $Z = -9.6012$ cm for both the unpoisoned and the poisoned lattices. A simple arithmetic mean of the resulting four calculated to measured region normalization factors was then used to normalize all ANISN values. The re-normalized ANISN values then fit the measured data to within a maximum error of 4.4% and 1.3%, respectively, for the unpoisoned and poisoned lattices. The similarly normalized values for the cladding, with the above errors assigned, were then used as the inferred sub cadmium foil data at $Z = -9.6012$ cm.

4.5.3 Cell-Averaged Copper Activation Rate Distribution

After a complete set of activation data had been obtained for each region at -9.6012 cm from the axial center of the test cell, some method of converting these values to axial averages was needed. Sufficient measured axial data had been obtained through the target and target end caps to directly obtain the sub cadmium axial averages for these regions by graphic integration of the plots in Figures 7 and 8. Complete axial data were not available for the other material regions. However, as mentioned previously, enough measured data were available to establish that the activation distributions calculated using two-dimensional transport theory, agreed quite well with experiment. The measured and calculated ratios of the axial average to the -9.6012 cm sub-cadmium target activity agreed to within 0.1% and 0.5%, respectively, for the unpoisoned and poisoned lattices. Based on these comparisons, use of the calculated ratios to obtain the remaining axial averages was justified. Defining this ratio as R , the fitted axial cosine as f , and the transport theory radially averaged ^{63}Cu activation for 0.010 inch thick copper foils as A , then

$$R_x^i(Z_o) = \overline{fA_x^i} / f(Z_o) A_x^i(Z_o),$$

where i is used to identify the material region and x denotes either epi- or sub-cadmium. The calculated values of $\overline{fA_x^i}$, where

$$\overline{fA_x^i} = \int f(Z) A_x^i(Z) dZ / \int dZ,$$

were obtained by simple trapezoidal integration. The calculated ratios for $Z_o = -9.6012$ cm are tabulated in Table VII.

TABLE VII

Calculated^a Ratios of the Axially Averaged Activity to
the Activity at Z = -9.6012 cm. for 0.010 In. Thick Copper Foils

i	Region	<u>Unpoisoned Lattice</u>		<u>Poisoned Lattice</u>	
		R_{Cd}^i	$R_{sub\ Cd}^i$	R_{Cd}^i	$R_{sub\ Cd}^i$
1	Target	0.9574	0.9708 ^b	0.9657	0.9793 ^c
2	Target Al Clad	0.9567	0.9710	0.9653	0.9799
3	Target Zr Clad	0.9566	0.9718	0.9652	0.9806
4	Inner Moderator	0.9574	0.9670	0.9652	0.9758
5	Fuel Inner Zr Clad	0.9566	0.9641	0.9652	0.9728
6	Fuel	0.9567	0.9615	0.9653	0.9702
7	Fuel Outer Zr Clad	0.9568	0.9601	0.9654	0.9705
8	Outer Moderator	0.9568	0.9589	0.9654	0.9676

a. 2-D transport theory (DOT) with superimposed fitted axial cosine

b. The measured value is 0.9699

c. The measured value is 0.9749

Finally, the "measured" axial averages, except for the target region sub cadmium values, were obtained from

$$\overline{SA}_x^i = R_x^i(Z_o) SA_x^i(Z_o), \quad Z_o = -9.6012 \text{ cm.}$$

The resulting region averaged activities are tabulated in Table VIII.

TABLE VIII

Axially Averaged Region Activities for 0.010 Inch Thick Copper Foils

A. Unpoisoned Lattice

<u>Region</u>	<u>SA_B⁶³</u>	<u>SA_{Cd}⁶³</u>	<u>SA_{Sub Cd}⁶³</u>	<u>SA_{1/v}⁶³</u>
Target	1.70453	0.48700	1.21753	1.47232
Target Al Clad	2.01602	0.49438	1.52164	1.78029
Target Zr Clad	2.08565	0.49701	1.58864	1.84867
Inner Moderator	2.48739	0.49821	1.98918	2.24984
Fuel Inner Zr Clad	2.16743	0.48792	1.67951	1.93478
Fuel	2.27470	0.48189	1.79281	2.04493
Fuel Outer Zr Clad	2.82575	0.50297	2.32278	2.58593
Outer Moderator	4.97905	0.52844	4.45061	4.72708
Target Al End Caps	2.33868	0.48290	1.85578	2.10843

B. Poisoned Lattice

Target	1.01316	0.30610	0.70706	0.86766
Target Al Clad	1.30378	0.31078	0.99300	1.15560
Target Zr Clad	1.34518	0.31251	1.03267	1.19617
Inner Moderator	1.44630	0.31277	1.13353	1.29717
Fuel Inner Zr Clad	1.32762	0.30653	1.02109	1.18146
Fuel	1.33754	0.30284	1.03470	1.19314
Fuel Outer Zr Clad	1.75721	0.31592	1.44129	1.60658
Outer Moderator	2.74431	0.33186	2.41245	2.58608
Target Al End Caps	1.39250	0.30583	1.08667	1.53832

4.6 Cross Sections Used in the Analysis

Thermal spectrum-averaged cross sections were obtained from the integral transport theory thermalization code, THERMOS,⁽¹⁰⁾ modified to use a "white" cell boundary condition. The thermal cross sections for each isotope in each region are presented in Tables IX and X for the unpoisoned and poisoned lattices, respectively.

Cell material cross sections utilized in the transport theory calculations were generated using THERMOS and the slowing down code EGGNIT.⁽¹¹⁾ Both the one-dimensional ANISN⁽¹²⁾ and the two-dimensional DOT⁽¹³⁾ discrete ordinate transport theory codes were used in the data fitting process. The transport theory copper activation cross sections were obtained from THERMOS, EGGNIT and HRG.⁽¹⁴⁾ Region-averaged ^{63}Cu values from THERMOS were used for the thermal group cross sections for all the copper detectors. Where necessary in the analysis, the transport theory sub-cadmium activation distributions were corrected for the difference in the point and region-averaged thermal activation cross sections. HRG, with the fine group lattice flux and current results from EGGNIT as input, was used to obtain the size and shape dependent epithermal activation cross sections for the copper detectors. A five energy group model was employed to allocate ^{238}U fast fission and resonance absorption into four "fast" groups. The group structure and its rationale are described in Table XI.

TABLE IX

Unpoisoned Lattice THERMOS Cross Sections

Reg.	Isotope	$\bar{\sigma}_a$	$\bar{\sigma}_{1/v}$	$\hat{\sigma}_a$	N	$\hat{\Sigma}_a$
1	${}^6\text{Li}$	5.49822+2	5.82439-1	944.00000	5.7576-4	.543517
1	${}^7\text{Li}$	1.92205-2		0.03300	1.5237-2	.000503
1	Al	1.36873-1		0.23500	1.8235-2	.004285
1	O	1.03674-4		0.00018	3.5304-2	.000006
2	Al	1.50779-1	6.41611-1	0.23500	6.0271-2	.014164
3	Zr	1.21002-1	6.43630-1	0.18800	4.2500-2	.007990
4	H	2.18263-1	6.57419-1	0.23200	6.6800-2	.022178
4	O	1.17021-4		0.00018	3.3400-2	.000006
5	Zr	1.19593-1	6.36133-1	0.18800	4.2500-2	.007990
6	${}^{235}\text{U}$	4.00102+2	6.26584-1	638.5449	1.0048-3	.641610
6	${}^{238}\text{U}$	1.72418+0		2.75171	4.6612-2	.128263
7	Zr	1.28643-1	6.84269-1	0.18800	4.2500-2	.007990
8	H	2.54161-1	7.65544-1	0.33200	6.6800-2	.022178
8	O	1.36267-4		0.00018	3.3400-2	.000006
9	Al			0.23500	5.2325-2	.012296
Copper	} ${}^{63}\text{Cu}$				5.8538-2	.263421
Detector					2.6189-2	.059187

TABLE X

Poisoned Lattice THERMOS Cross Sections

Reg.	Isotope	$\bar{\sigma}_a$	$\bar{\sigma}_{1/v}$	$\hat{\sigma}_a$	N	$\hat{\Sigma}_a$
1	${}^6\text{Li}$	5.37859+2	5.69766-1	944.00000	5.7576-4	.543517
1	${}^7\text{Li}$	1.88023-2		0.03300	1.5237-2	.000503
1	Al	1.33895-1		0.23500	1.8235-2	.004285
1	O	1.01418-4		0.00018	3.5304-2	.000006
2	Al	1.47452-1	6.27455-1	0.23500	6.0271-2	.014164
3	Zr	1.18367-1	6.29614-1	0.18800	4.2500-2	.007990
4	H	2.13663-1	6.43562-1	0.33200	6.6800-2	.022178
4	B	4.88464+2		759.00000	3.0642-5	.023257
4	O	1.14554-4		0.00018	3.3400-2	.000006
5	Zr	1.16942-1	6.22030-1	0.18800	4.2500-2	.007990
6	${}^{235}\text{U}$	3.90080+2	6.12386-1	636.98400	1.0048-3	.640042
6	${}^{238}\text{U}$	1.68658+0		2.75411	4.6612-2	.128375
7	Zr	1.25704-1	6.68638-1	0.18800	4.2500-2	.007990
8	H	2.48924-1	7.49770-1	0.33200	6.6800-2	.022178
8	B	5.69075+2		759.00000	3.0642-5	.023257
8	O	1.33459-4		0.00018	3.3400-2	.000006
9	Al			0.23500	5.2325-2	.012276
Copper	} ${}^{63}\text{Cu}$				5.8538-2	.263421
Detector					2.6189-2	.059187

TABLE XIEnergy Group Structure Used In
Transport Theory Calculations

<u>Group Number</u>	<u>Energy Boundaries</u>	<u>Rational</u>
1	10 MeV-1.05 MeV	Contains All ^{238}U Fast Fission
2	1.05 MeV-11.7 KeV	Groups 1 and 2 Contain total prompt fission source.
3	11.7 KeV-8.38 eV	Major portion of ^{238}U Resonance Region
4	8.38 eV-0.683 eV	Contains 1st (and major) ^{238}U Resonance @ 6.67 eV
5	0.683 eV-0 eV	Thermal Group, Upper Boundary is ~ cadmium cut-off for 40 mil Cd.

4.7 Determination of ^{63}Cu 1/v Absorption Rates

The total and epicadmium copper detector activation results include epithermal non-1/v contributions from ^{63}Cu resonance absorptions. The total 1/v activation rate is inferred from the following expression

$$SA_{1/v}^{63} = SA_B^{63} - (RI_{\text{Ex}}/RI_{\text{Epi-Cd}})^{63} SA_{\text{Cd}}^{63}$$

where $(RI_{\text{Ex}}/RI_{\text{Epi-Cd}})^{63}$ is the ratio of the excess to total epicadmium resonance integrals for ^{63}Cu . The values of this ratio are inferred from Bennett's measurements of these integrals for various foil thicknesses. (15,16) However, no such measured data was available for copper pins. HRG was therefore used to calculate RI_{Ex}^{63} for 0.036 inch diameter pins and for various thicknesses of copper foils. These calculations showed that an equivalent foil thickness of 0.0162 inches gave the same RI_{Ex}^{63} as the 0.036 inch diameter pin. The resonance integral ratio for 0.036 inch pins was then taken from Bennett's data at the equivalent foil thickness of 0.0162 inches. The values of the ratio for this pin and the two primary foil thicknesses used in this experiment are tabulated below.

<u>Detector</u>	<u>$(RI_{\text{Ex}}/RI_{\text{Epi-Cd}})^{63}$</u>
0.005 in. foils	0.5132
0.010 in. foils	0.4768
0.036 in. pins	0.4454

4.8 Determination of 1/v Utilizations

The spatial distribution of the 1/v absorption rate density in ^{63}Cu is given by

$$SA_{1/v}^{63}(r) = C \cdot N^{63} \hat{\sigma}_a^{63}(r) \int_0^\infty \sqrt{E_0/E} \phi(E, r) dE$$

where

$$\hat{\sigma}_a^{63}(r) = \frac{\int_0^{E_{co}} \sigma^{63}(E) \phi(E, r) dE}{\int_0^{E_{co}} \sqrt{E_0/E} \phi(E, r) dE} \quad (E_{co} = 0.683 \text{ eV}),$$

C is a space independent normalizing constant and N^{63} is the nuclear density of ^{63}Cu . Since a similar expression can be written for the spatial distribution of the 1/v absorption rate density in material X, we can infer this latter distribution from

$$SA_{1/v}^X(r) = \left[\hat{\Sigma}_a^X(r) / \hat{\Sigma}_a^{63}(r) \right] SA_{1/v}^{63}(r)$$

The total 1/v absorption rate in material X, $(\text{Abs.})_{1/v}^X$, in a region whose volume is V_i , is simply the volume integral of $SA_{1/v}^X(r)$ over V_i or

$$(\text{Abs.})_{1/v}^X = \int_{V_i} SA_{1/v}^X(r) dV$$

The $1/v$ utilization of a cell component is defined as the ratio of the $1/v$ absorption rate in that component to the sum of $1/v$ absorption rates in all cell components. With this definition the $1/v$ utilization of material X is

$$f_{1/v}^X = (\text{Abs.})_{1/v}^X / \sum_i (\text{Abs.})_{1/v}^i .$$

The $1/v$ absorption rates and $1/v$ utilizations of each cell region are tabulated in Tables XII and XIII for the unpoisoned and poisoned cases.

TABLE XII

Experimental Relative 1/v Absorption RatesA. Unpoisoned Lattice

<u>Region</u>	<u>Volume (cm³)</u>	<u>$\hat{\Sigma}_a$ (cm⁻¹)</u>	<u>SA⁶³_{1/v}</u>	<u>% Error</u>	<u>Relative 1/v Absorptions</u>
Target	336.5063	0.548311	1.46232	0.586	1031.2689 $\pm$ 6.0535
Target Al Clad	142.5877	0.014164	1.78029	4.412	13.6492 $\pm$ 0.6022
Target Zr Clad	46.7417	0.007990	1.84867	4.412	2.6210 $\pm$ 0.1156
Inner Moderator	354.9636	0.022184	2.24984	0.509	67.2550 $\pm$ 0.3423
Fuel Inner Zr Clad	54.1227	0.007990	1.93478	4.412	3.1762 $\pm$ 0.1401
Fuel	697.9688	0.769873	2.04498	0.481	4171.4129 $\pm$ 20.0645
Fuel Outer Zr Clad	95.9603	0.007990	2.58593	4.412	7.5267 $\pm$ 0.3321
Outer Moderator	1469.7742	0.022184	4.72708	0.295	585.1040 $\pm$ 1.7261
Target Al End Caps	14.2941	0.012296	2.10843	5.000	1.4068 $\pm$ 0.0703
Total				0.358	5883.4208 $\pm$ 21.0437

$$f_{1/v} = 0.709011 \pm 0.00425 \text{ (0.600\%)}$$

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TABLE XII (Continued)

B. Poisoned Lattice

<u>Region</u>	<u>Volume (cm³)</u>	<u>$\hat{\Sigma}_a$ (cm⁻¹)</u>	<u>SA⁶³_{1/v}</u>	<u>% Error</u>	<u>Relative 1/v Absorptions</u>
Target	336.5063	0.548311	0.86766	0.152	607.7421 ± 0.9238
Target Al Clad	142.5877	0.014164	1.15560	1.320	8.8598 ± 0.1169
Target Zr Clad	46.7417	0.007990	1.19617	1.320	1.6959 ± 0.0224
Inner Moderator Water	354.9636	0.022184	1.29717	0.470	38.7766 ± 0.1823
Inner Moderator Boron	354.9636	0.023257	1.29717	2.232	40.6522 ± 0.9074
Fuel Inner Zr Clad	54.1227	0.007990	1.18146	1.320	1.9395 ± 0.0256
Fuel	697.9688	0.768417	1.19314	0.354	2429.2601 ± 8.5996
Fuel Outer Zr Clad	95.9603	0.007990	1.60658	1.320	4.6762 ± 0.0617
Outer Moderator Water	1469.7742	0.022184	2.58608	0.247	320.0974 ± 0.7906
Outer Moderator Boron	1469.7742	0.023257	2.58608	2.196	335.5799 ± 7.3693
Target Al End Caps	14.2941	0.012296	1.53832	0.215	1.0264 ± 0.0022
Total				0.302	3790.3061 ± 11.4286

$$f_{1/v}^{\wedge} = 0.640914 \pm 0.00298 \text{ (0.465\%)}$$

TABLE XIIIExperimental 1/v Utilizations

	<u>Unpoisoned</u>	<u>Poisoned</u>
Target	0.17528 ± 0.00120	0.16034 ± 0.00054
Target Al Clad	0.00232 ± 0.00010	0.00234 ± 0.00003
Target Zr Clad	0.00045 ± 0.00002	0.00045 ± 0.00001
Inner Moderator Water	0.01143 ± 0.00007	0.01023 ± 0.00006
Inner Moderator Boron	---	0.01073 ± 0.00025
Fuel Inner Zr Clad	0.00054 ± 0.00002	0.00051 ± 0.00001
Fuel	0.70901 ± 0.00425	0.64091 ± 0.00298
Fuel Outer Zr Clad	0.00128 ± 0.00006	0.00123 ± 0.00002
Outer Moderator Water	0.09945 ± 0.00046	0.08445 ± 0.00033
Outer Moderator Boron	---	0.08854 ± 0.00196
Target Al End Caps	0.00024 ± 0.00001	0.00027 ± 0.00001

4.9 Determination of k_{∞}

The basis for the determination of k_{∞} from these measurements is the assumption that the addition of boron to the moderator produces changes in only the $1/v$ utilization^(4,5). Thus with the null reactivity boron concentration present in the cell we have in terms of the "four factor formula,"

$$k'_{\infty} = \eta \epsilon p f' = 1$$

which allows us to determine k_{∞} from

$$k_{\infty} = \frac{f}{f'}$$

where

f = fuel $1/v$ utilization in the unpoisoned cell

f' = fuel $1/v$ utilization in the poisoned cell.

When calculating these $1/v$ utilizations it is assumed that absorption rates in all cell components, except for resonance absorption, can be represented by effective $1/v$ cross sections and the relative fluxes in each cell component can be determined from the activation of a " $1/v$ detector."

Thus, the use of the four factor formula in the derivation of k_{∞} implies that the resonance escape probability accounts for all the non $1/v$ epithermal absorption.

The "inferred from measurement" infinite multiplication for this lattice then is

$$k_{\infty} = \frac{0.709011 \pm 0.004254}{0.640914 \pm 0.002980} = 1.10625 \pm 0.00840$$

5. ADDITIONAL CORRECTION METHODS AND SYSTEMATIC ERRORS

In this section, the method of correcting the cell-out reactivity measurements for the presence of nitrogen in the void region is outlined followed by the methods and results of counter efficiency and flux perturbation (for both foils and pins) corrections to the copper activation data. At the end of this section the end effect is defined and identified as a highly probable cause of a systematic error in the measurement for this lattice.

5.1 Nitrogen Corrections

Nitrogen affects the null reactivity measurement in that the center cell is not completely void in the cell-out condition, but instead contains air at ambient pressure and temperature. Corrections for nitrogen absorptions in the cell-out case are therefore necessary in order to determine the cell worth and the just critical boron concentration.

The reactivity worth, $\Delta\rho_N$, of the nitrogen which fills the cavity formed by removal of the central cell is inferred from a copper sensitivity measurement using the expression:

$$\Delta\rho_N = DC \frac{P}{T} (M_N) (1-c) S_{Cu}^{cavity}$$

where D = thermal disadvantage factor for the thickness of copper used in the determination of S_{Cu}^{cavity}

$$S_{Cu}^{cavity} = \Delta\rho_{Cu}^{cavity} / M_{Cu}^{cavity}, \text{ } \epsilon/\text{gram of copper};$$

$$\Delta\rho_{Cu}^{cavity} = \text{worth of mass of copper, } M_{Cu}^{cavity}, \text{ in the cell cavity, } \epsilon;$$

P = atmospheric pressure during reactivity measurement, mb;

T = ambient temperature in cavity during reactivity measurement, $^{\circ}\text{K}$;

M_N = mass of nitrogen (at standard temperature and pressure) in cavity

$$C = \frac{\sigma_o^N}{\sigma_o^{Cu}} \frac{A_{Cu}}{A_N} \frac{T_o}{P_o}$$

σ_o^N = 2200 m/sec microscopic absorption cross section of nitrogen.

σ_o^{Cu} = 2200 m/sec microscopic absorption cross section of natural copper.

$A^{\text{Cu}}, A^{\text{N}}$ = copper and nitrogen atomic weights.

T_o, P_o = standard temperature and pressure.

The quantity $(1-c)$ is a correction for the non- $1/v$ nature of the epithermal energy dependence of the absorption cross section of natural copper approximated by:

$$(1 - c) = 1 - \left(\frac{m_1}{m_2} \right) \frac{RI_{\text{ex}}^{\text{Cu}}}{RI_{\text{epi-Cd}}^{\text{Cu}} (\text{CdR} - 1)}$$

where $\frac{m_1}{m_2}$ = ratio of the fast-to-thermal adjoint fluxes and is approximately equal to the resonance escape probability of the test lattice.

$RI_{\text{ex}}^{\text{Cu}}$ = effective excess resonance integral of natural copper for the thickness of copper used in measuring $S_{\text{Cu}}^{\text{cavity}}$

$RI_{\text{epi-Cd}}^{\text{Cu}}$ = effective epi-cadmium resonance integral of natural copper for the thickness of copper used in measuring $S_{\text{Cu}}^{\text{cavity}}$

CdR = cadmium ratio of copper in the cavity, for the thickness of copper used in measuring $S_{\text{Cu}}^{\text{cavity}}$

5.2 Counter Efficiency Corrections

The observed average specific activity for a foil of a given shape counted at a given vertical distance h from the detector surface can be written in terms of a detector response function (or efficiency function) as

$$\bar{A} = \frac{\int_{\text{foil}} \epsilon(\vec{\rho}) A_o(\vec{\rho}) dV}{\int_{\text{foil}} dV}$$

where $\epsilon(\vec{\rho})$ is the detector response function and $A_o(\vec{\rho})$ is the spatially varying activity per unit mass.

FIGURE 10. COUNTER GEOMETRY

Assuming the axial variations across the foil thickness can be neglected, the observed average specific activity at a given height can be rewritten in terms of the radial response function as

$$\bar{A} = \frac{\int_{\text{foil}} \epsilon(\vec{r}) A_o(\vec{r}) dV}{\int_{\text{foil}} dV}$$

where r is the distance in the foil plane from the crystal axis.

In our case, the quantity actually observed is the relative average specific activity, which is the ratio of the specific activity of a particular foil irradiated at some lattice position to that of another foil of nearly identical shape irradiated on a rotator in the thermal column. These foils are always irradiated at the same time and counted at the same position relative to the detector.

The sector foils used to determine the relative reaction rate in the major cell regions have the largest spatial variation of the specific activity. On the other hand, the specific activity of the corresponding normalizing foils (from the thermal column) do not vary with position.

The relative activity can also be written in terms of the efficiency response function, i.e.,

$$SA \equiv \frac{\bar{A}^L}{\bar{A}^{TC}} = \frac{\int_L A_o^L(\vec{r}) \epsilon(\vec{r}) dV / \int_L dV}{\int_{TC} A_o^{TC}(\vec{r}) \epsilon(\vec{r}) dV / \int_{TC} dV}$$

where L and TC are used, respectively, to denote the lattice and thermal column foils. The expression above for SA can be rewritten as

$$SA = (\bar{A}^L / \bar{A}^{TC}) = (\bar{A}_O^L \bar{\epsilon}^L / \bar{A}_O^{TC} \bar{\epsilon}^{TC}) = SA_O (\bar{\epsilon}^L / \bar{\epsilon}^{TC})$$

where

$$SA_O \equiv A_O^L / A_O^{TC},$$

$$\bar{A}_O^{TC} = A_O^{TC}(\vec{r}) = \text{constant},$$

$$\bar{\epsilon}^{TC} = \int_{TC} \epsilon(\vec{r}) dV / \int_{TC} dV,$$

$$\bar{A}_O^L = \int_L A_O(\vec{r}) dV / \int_L dV,$$

and

$$\bar{\epsilon}^L = \int_L \epsilon(\vec{r}) A_O^L(\vec{r}) dV / \int_L A_O^L(\vec{r}) dV.$$

Thus in order to obtain the true activity ratio from the observed value,

$$SA_O = SA (\bar{\epsilon}^{TC} / \bar{\epsilon}^L)$$

we need to know $A_O^L(r)$ and the relative dependence of $\epsilon(r)$ on r .

The relative radial variation of the efficiency functions for the detectors used in this experiment had previously been measured by Bennett⁽²⁰⁾ at several vertical positions using a ^{137}Cs point source. The relative efficiency function for the counting geometry was obtained from this data. The procedure used to obtain the sector efficiency corrections $(\bar{\epsilon}^{TC} / \bar{\epsilon}^L)$ is outlined below:

- i. A sector foil for a given region was dissected into n annular subregions.
- ii. Each subregion was counted in exactly the same position with respect to the detector that it would occupy had the whole sector been counted.
- iii. Each subregion i of the given sector was normalized to the same whole sector from the thermal column; i.e.,

$$SA_i = \bar{A}_i / \bar{A}^{TC}.$$

- iv. The dissected subregions were superimposed on the detector efficiency topographical plots just as they were counted in order to obtain an average efficiency for each subregion; i.e.,

$$\epsilon_i = \int_{V_i} \epsilon(\vec{r}) dV / \int_{V_i} dV$$

where V_i is the volume of subregion i .

- v. The average efficiency for the thermal column sector was obtained

from

$$\bar{\epsilon}^{TC} = \sum_{i=1}^r \epsilon_i V_i / \sum_{i=1}^r V_i$$

- vi. The efficiency corrected specific activity for each subregion i was found from

$$SA_{O_i} = SA_i (\bar{\epsilon}^{TC} / \epsilon_i).$$

- vii. The ratio of efficiency's for the given sector is finally found from

$$\left(\frac{\epsilon^{-TC}}{\epsilon^{-L}}\right) = \frac{\sum_{i=1}^n SA_{o_i} V_i}{\sum_{i=1}^n SA_i V_i}$$

The 30° sector foils and their subregions used in this experiment for the major cell components can be seen in Figure 11, along with the corresponding dimensions. The resulting efficiency corrections for each sector foil in the two lattices is summarized in Table XIV along with the corresponding one standard deviation percentage error and the average efficiencies for the normalizing thermal column sectors.

TABLE XIV

Sector Foil Counter Efficiency Correction Factors

<u>Sector</u>	$\left(\frac{\epsilon^{-TC}}{\epsilon^{-L}}\right)$		$\frac{-TC}{\epsilon}$
	<u>Unpoisoned</u>	<u>Poisoned</u>	
Target	0.99997(.340)	0.99998(.298)	0.99164
Inner Moderator	0.99999(.430)	1.00000(.402)	0.99403
Fuel	1.00023(.312)	1.00020(.281)	0.98670
Outer Moderator	1.00036(.249)	1.00047(.199)	0.97815

As can be seen from the table, the efficiency correction is in fact negligible for all sectors. This is primarily due to the fact that the foils were carefully positioned with their centroid on the detector axis using specially designed foil holders. This placed the approximate point of average activity at the relative efficiency functions point of symmetry.

5.3 Flux Perturbation Corrections for Foils

The presence of the detector foils used to measure the relative reaction rates in cell components produces a perturbation in the flux in the medium in the vicinity of the foil as well as a depression of the flux in the foil itself. This flux peaking or dipping in finite thickness foil

FIGURE 11. DISECTED SECTOR FOILS

detectors is primarily a function of the thickness of the foil and the medium in which the foil is placed. The magnitude of the perturbation is proportional to the difference in the macroscopic absorption cross section of the foil and the medium⁽¹⁷⁾. A reasonably accurate and relatively simple relationship, assuming an isotropic flux and neglecting foil edge effects, between a measured activity, A_{foil} , and the activity, A_o , which would have resulted had the foil not perturbed the flux was derived in Reference 17 to be:

$$A_o = A_{\text{foil}} \left\{ 1 - t \left(\sum_{\text{medium}} - \sum_{\text{foil}} \right) \ln \beta / t \right\} \quad (1)$$

where

$$\beta \begin{cases} L = \text{foil width for square foils} \\ D = \text{foil diameter for round foils} \end{cases}$$

t = foil thickness

$\sum_{\text{medium}}$ = macroscopic absorption cross section of the medium in which the foil is placed.

$\sum_{\text{foil}}$ = macroscopic absorption cross section of the foil.

Corrections to the measured round, square and sector foil sub-cadmium activities in the cell were made using this relationship and employing region (or point, if appropriate) averaged thermal cross sections from THERMOS. Thermal column foil activities were corrected in a similar fashion with cross sections being averaged over an essentially thermal neutron energy spectrum in THERMOS.

5.4 Flux Perturbation Corrections for Pins

Since copper pins were used in this experiment to get "point" activation traverses, a method of correcting the pin activities for thermal flux peaking or depression was needed. It was decided to directly apply the same relationship that was used for foils by obtaining an approximate equivalence relationship between finite slabs and cylinders. What follows is the determination of the approximate equivalence relationships (actually two are involved) required to apply the correction to pins and a summary of the resulting procedure for actually using this method.

Equivalence Relationships

Two equivalence relationships are needed to directly apply Equation (1) to pin activities. The first, establishing a cylindrical equivalent to β/t , is obtained using mean chord length arguments; the second, obtaining explicitly the cylindrical equivalent to the slab thickness t , is obtained primarily using self-shielding arguments.

β/t Equivalence

The mean chord lengths for infinite slabs and cylinders are, respectively;

$$\overline{l}_{\text{slab}}^{\infty} = 2t \quad (2)$$

and

$$\overline{l}_{\text{cyl}}^{\infty} = 2r. \quad (3)$$

If the ratio of these mean chord lengths is defined as C_{∞} , then

$$C_{\infty} \equiv \frac{\overline{l}_{\text{slab}}^{\infty}}{\overline{l}_{\text{cyl}}^{\infty}} = \frac{t}{r} \quad (4)$$

Keeping this definition in mind, we will consider both round and square foils, since β can refer to either

Square Foils

The mean chord lengths for finite slabs (square foils) and cylinders (pins) are, respectively,

$$\bar{\ell}_{\text{slab}} = \frac{4t L^2}{2 L^2 + 4Lt} = \frac{2t}{1 + \frac{2t}{L}} \quad (5)$$

where L is the width and t the thickness,

$$\text{and } \bar{\ell}_{\text{cyl}} = \frac{4\pi r^2 h}{2\pi rh + 2\pi r^2} = \frac{2r}{1 + \frac{r}{h}} \quad (6)$$

where h is the height and r the radius.

If the ratio of the finite mean chord lengths is now defined as C , the

$$C \equiv \frac{\bar{\ell}_{\text{slab}}}{\bar{\ell}_{\text{cyl}}} = \frac{t}{r} \left[\frac{1 + \frac{r}{h}}{1 + \frac{2t}{L}} \right] \quad (7)$$

In the limit as h and L go to infinity, C becomes C_{∞} . If r/h and $2t/L$ are both small, C_{∞} can be used as a reasonable approximation to C . Therefore, replacing C by C_{∞} in Equation (7) and solving for L/t results in

$$\frac{L}{t} = \frac{2h}{r} \quad (8)$$

Round Foils

The mean chord length for a disk of diameter D and thickness t is

$$\bar{\ell}_{\text{disk}} = \frac{4t \pi (D/2)^2}{2\pi (D/2)^2 + 2\pi (D/2)t} = \frac{2t}{1 + \frac{2t}{D}} \quad (9)$$

If $\bar{\ell}_{\text{disk}}$ is used instead of $\bar{\ell}_{\text{slab}}$ in an expression similar to Equation (7), i.e.,

$$C' \equiv \frac{t}{r} \left[\frac{1 + \frac{r}{h}}{1 + \frac{2t}{D}} \right] \quad (10)$$

and if, as before, C' is approximated by C_{∞} (C_{∞} remains unchanged since $\bar{\ell}_{\text{disk}}^{\infty} = \bar{\ell}_{\text{slab}}^{\infty}$), the resulting equation can be solved for D/t , giving

$$\frac{D}{t} = \frac{2h}{r} \quad (11)$$

The RHS of Equation (11) is the same as the RHS of Equation (8), so for a given thickness, D is equivalent to L . This is the same assumption Dunn⁽¹⁷⁾ used. Therefore, the first equivalence says

$$\frac{\beta}{t} = \frac{2h}{r} \quad (12)$$

Foil Thickness Equivalence

For small τ ($\tau \equiv \bar{\ell}_{\infty} \Sigma_t/2$), the self-shielding factors for infinite slabs and cylinders emersed in an isotropic flux can be approximated (neglecting scattering effects) as follows⁽¹⁸⁾

$$f_{\text{cyl}} \approx 1 - \frac{1}{2} \tau_{\text{cyl}} \left[\frac{8}{3} - \tau_{\text{cyl}} (\ln \tau_{\text{cyl}} + 1.365931) \right] \quad (13)$$

$$f_{\text{slab}} \approx 1 - \frac{1}{2} \tau_{\text{slab}} \left[.922784 - \ln \tau_{\text{slab}} + \frac{1}{3} \tau_{\text{slab}} \right] \quad (14)$$

where $\tau_{\text{slab}} = t \Sigma_t^{\text{foil}}$ and $\tau_{\text{cyl}} = r \Sigma_t^{\text{foil}}$. Therefore, given an infinite

cylinder of radius r , the equivalent thickness, t , of an infinite slab of the same material, which gives the same self shielding factor as the cylinder, can be found by simply equating Equations (13) and (14). The resulting expression

$$\tau_{\text{cyl}} \left[\frac{8}{3} - \tau_{\text{cyl}} (\ln \tau_{\text{cyl}} + 1.365931) \right] = \tau_{\text{slab}} \left[0.922784 - \ln \tau_{\text{slab}} + \frac{1}{3} \tau_{\text{slab}} \right] \quad (15)$$

also holds true if the usual scattering correction⁽¹⁸⁾ is made to the self-shielding factors

$$f_{\text{corr}} = \frac{f_o}{1 - C(1 - f_o)} \quad (16)$$

where $C = (\Sigma_s / \Sigma_t)^{\text{foil}}$. Equating the corrected self-shielding factors, i.e.,

$$\frac{f_{\text{cyl}}}{1 - C(1 - f_{\text{cyl}})} = \frac{f_{\text{slab}}}{1 - C(1 - f_{\text{slab}})} \quad (17)$$

and using Equations (13) and (14), respectively, for f_{cyl} and f_{slab} , results identically in Equation (15). It is possible to solve Equation 15 by iteration for τ_{slab} and hence t , but the resulting thickness would refer to an equivalent infinite slab instead of a finite one. For this reason a slightly different approach is used. Equations (13) and (14) are assumed to also hold for finite slabs and cylinders, which is in keeping with our previous assumptions of small r/h and $2t/L$. Equations (13) through (15) are, therefore, unchanged except for the definitions of the τ 's, which would be

$$\tau = \frac{1}{2} \frac{\Sigma_s}{\Sigma_t} \quad (18)$$

More specifically,

$$\tau_{\text{cyl}} = \frac{r \Sigma_t^{\text{pin}}}{1 + \frac{r}{h}} \quad (19)$$

and

$$\tau_{\text{slab}} = \frac{t \Sigma_t^{\text{pin}}}{1 + \frac{2t}{\beta}} \quad (20)$$

Substituting our first equivalence, Equation (12) into Equation (20) gives

$$\tau_{\text{slab}} = \frac{t \Sigma_t^{\text{pin}}}{1 + \frac{r}{h}} \quad (21)$$

Solving Equation (21) for t results in our second equivalence expression

$$t = \frac{(1 + \frac{r}{h}) \tau_{\text{slab}}}{\Sigma_t^{\text{pin}}} \quad (22)$$

Pin Activity Correction

The desired result (a approximate flux peaking or dipping correction for pin shaped foils) is obtained by substituting Equations (12) and (22) into Equation (1), which then becomes

$$\left(\frac{A_o}{A} \right)_{\text{pin}} = 1 - \left(\frac{\Sigma_a^{\text{med}} - \Sigma_a^{\text{pin}}}{\Sigma_t^{\text{pin}}} \right) \tau_{\text{slab}} \left(1 + \frac{r}{h} \right) \ln \left(\frac{2h}{r} \right) \quad (23)$$

Finally, the following summarizes the simple procedure leading to $A_{\text{pin}}^{\text{corrected}}$:

1. Determine Σ_a^{pin} , Σ_t^{pin} , and Σ_a^{med}
2. Calculated τ_{cyl} from Equation (19)
3. Calculate the LHS of Equation (15) and then solve for τ_{slab} by iteration

4. Calculate $(A_o/A)_{pin}$ from Equation (23)
5. Correct the measured activity via $A_{pin}^{corrected} = A_{pin}^{meas.} (A_o/A)_{pin}$

Added Comments

Since the results here are based on monenergetic considerations, Equation (23) actually expresses the energy dependent ratio of the unperturbed to the perturbed flux, $\phi_o(E)/\phi(E)$. The proper spectrum weighted form of Equation (23) can be shown to be

$$\frac{A_o}{A} = \left[\left\langle \frac{1}{1 - (1 + \frac{r}{h}) \ln(\frac{2h}{r}) \beta(E)} \right\rangle_{act} \right]^{-1} \quad (24)$$

where

$$\left\langle \frac{1}{1 - (1 + \frac{r}{h}) \ln(\frac{2h}{r}) \beta(E)} \right\rangle_{act} = \frac{\int \left[1 - (1 + \frac{r}{h}) \left\{ \ln(\frac{2h}{r}) \right\} \beta(E) \right]^{-1} \phi^{med}(E) \Sigma_{act}^{pin}(E) dE}{\int \phi^{med}(E) \Sigma_{act}^{pin}(E) dE} \quad (25)$$

and

$$\beta(E) \equiv \frac{\tau_{slab}(E)}{\Sigma_t^{pin}(E)} \left(\Sigma_a^{med}(E) - \Sigma_a^{pin}(E) \right). \quad (26)$$

For estimating purposes, the simple five step procedure can be retained by using unperturbed spectrum averaged cross sections.

5.4.1 Activity Correction Method for Copper Pin Data on Outer Fuel Clad Surface

The APDAC bare and cadmium covered copper pin activities for the pins irradiated on the outer fuel clad surface are tabulated in Table XV for both the poisoned and unpoisoned lattices. The associated percentage error quoted in the table represents one standard deviation.

TABLE XV

Uncorrected Bare and Cadmium Covered Copper Pin Activities On Outer Fuel Clad Surface

A(cm) ^a	Unpoisoned Lattice				Poisoned Lattice			
	SA _B (r ₁ ,Z) ± (%)		SA _{Cd} (r ₂ ,Z) ± (%)		SA _B (r ₁ ,Z) ± (%)		SA _{Cd} (r ₂ ,Z) ± (%)	
-29.60	3.09653	(.458)	0.43695 ^(a)		1.76394	(.348)	0.28413	(.531)
-25.40	3.24770	(.455)	0.47692	(.398)	1.71934	(.350)	0.30086	(.519)
-20.32	3.41536	(.453)	0.53215	(.383)	1.81712	(.347)	0.32313	(.504)
-15.24	3.52097	(.451)	0.54345	(.381)	1.94360	(.359)	0.33654	(.497)
-10.16	3.63010	(.459)	0.56861	(.375)	1.98777	(.341)	0.34826	(.491)
- 5.08	3.77917	(.457)	0.58283	(.372)	2.00862	(.341)	0.34982	(.490)
0.00	3.87774	(.455)	0.58419	(.372)	2.10232	(.338)	0.35911	(.470)
5.08	3.75124	(.457)	0.57739	(.374)	2.04832	(.340)	0.35115	(.474)
10.16	3.63619	(.459)	0.55913	(.379)	2.01310	(.341)	0.34160	(.480)
15.24	3.60513	(.460)	0.54342	(.383)	1.87276	(.346)	0.33418	(.484)
20.32	3.44766	(.462)	0.52125	(.388)	1.87813	(.346)	0.32561	(.490)
25.40	3.24457	(.466)	0.48981	(.429)	1.77113	(.361)	0.30639	(.502)
29.60	3.14282	(.468)	0.45242	(.408)	1.83334	(.347)	0.29152	(.513)

r₁ = 3.0907 cm, r₂ = 3.1923 cm^a_{inferred}

These uncorrected specific activities needed to be corrected for the radial position difference between the bare and the cadmium covered pins on the fuel clad surface and for the flux depression in the pins in the lattice and the normalizing pin in the thermal column. The radial position correction factor, C_p , was calculated from the transport theory fast activation distribution for 0.036 in. diameter copper pins.

$$C_p(Z) = \left[A_{\text{fast}}^{63}(r_1, Z) / A_{\text{fast}}^{63}(r_2, Z) \right]^{36\text{mil Cu.}}$$

As calculated by the DOT Sn code, C_p proved to be independent of Z . The cadmium covered specific activity at the same radial position as the bare pin (r_1), then was found from

$$SA_{\text{Cd}}(r_1, Z) = C_p SA_{\text{Cd}}(r_2, Z),$$

where the calculated values of C_p were 0.98494 for the unpoisoned lattice and 0.98560 for the poisoned lattice. The uncertainty caused by such a correction is usually proportional to the magnitude of the correction; therefore, the cadmium covered data, because of its smaller radial gradient, was corrected to the radial position of the bare pins instead of vice versa. After the position corrections were made, the epi- and sub-cadmium pin activities were corrected in the usual manner for the flux peaking or dipping caused by the pin; ie.,

$$SA_{\text{Sub Cd}}^{63} = (SA_B^{\text{uc}} - SA_{\text{Cd}}^{\text{uc}}) \left[\frac{(A_o/A)_L}{(A_o/A)_{\text{TC}}} \right]$$

$$SA_{\text{Cd}}^{63} = SA_{\text{Cd}}^{\text{uc}} / (A_o/A)_{\text{TC}}$$

where the superscript, uc, has been used to denote the uncorrected (for peaking or dipping) value and the subscripts, L, for lattice and, TC, for thermal column differentiate between the two peaking or dipping corrections. The Dunn approximation, modified for pin shaped detectors as described previously, was used to obtain these corrections. Their values are tabulated below.

<u>Lattice Radius (cm)</u>	<u>Description</u>	<u>A_o/A</u>
--	Thermal Column	1.0186
3.0907	Unpoisoned Lattice	1.0134
3.0907	Poisoned Lattice	1.0120

5.4.2 Activity Correction Method for Copper Pins Partially Contained By A Plexiglass Holder in Outer Moderator

The 0.036 inch diameter by 0.25 inch long copper pins irradiated in the moderator were held in position by a sandwich-type plexiglass holder. A cross sectional view of a typical arrangement of pin, moderator and pin holder is depicted in Figure 12. A method was needed to correct the measured pin activities, listed in Table XVI, for the thermal flux perturbations caused by both the plexiglass pin holder and the pins themselves.

If the average thermal activation cross section of the copper pins (Σ_{act}) is assumed to be the same for the portion of the pin in the plexiglass as that in the unperturbed moderator, then the measured and unperturbed pin activities, respectively can be written as:

FIGURE 12. PLEXIGLASS PIN HOLDER

TABLE XVI

Uncorrected Bare and Cadmium Covered Copper Pin Activities
in Outer Moderator

A. Unpoisoned Lattice (Z=+9.6012cm)

<u>R (cm)</u>	<u>θ</u>	<u>$SA_B^{uc} \pm (\% \text{ Error})$</u>		<u>$SA_{Cd}^{uc} \pm (\% \text{ Error})$</u>	
3.17500	30°	4.19005	(.451)	0.55646	(.381)
3.66268	30°	5.91680	(.436)	0.56956	(.377)
4.15036	30°	6.58976	(.432)	0.58419	(.374)
3.17500	17°46'	4.01550	(.454)	0.56690	(.379)
3.64998	17°46'	5.66972	(.438)	0.58861	(.374)
4.06400	17°46'	6.10800	(.435)	0.59202	(.5) ^a
3.17500	0°	3.88742	(.456)	0.56300	(.381)
3.49250	0°	5.00351	(.443)	0.58050	(.377)
3.81000	0°	5.41034	(.440)	0.58484	(.375)

B. Poisoned Lattice (Z=+9.6012cm)

3.17500	30°	2.37372	(.346)	0.34364	(.482)
3.66268	30°	3.38779	(.327)	0.35058	(.479)
4.15036	30°	3.86517	(.321)	0.35626	(.476)
3.17500	17°46'	2.31801	(.347)	0.35192	(.479)
3.64998	17°46'	3.26870	(.328)	0.35989	(.475)
4.06400	17°46'	3.59753	(.324)	0.36329	(.5) ^a
3.17500	0°	2.19200	(.350)	0.34264	(.485)
3.49250	0°	2.77362	(.336)	0.34829	(.482)
3.81000	0°	3.00951	(.332)	0.35751	(.478)

^a_{inferred}

$$A = 1/2 \Sigma_{\text{act}} V_{\text{pin}} (\phi_p' + \phi_m') \quad (1)$$

and

$$A_o = \Sigma_{\text{act}} V_{\text{pin}} \phi_m, \quad (2)$$

where ϕ_p' is the average flux in the portion of the pin in the plexiglass, ϕ_m' is the average flux in the portion of the pin in the moderator, and ϕ_m is the unperturbed flux in the moderator. Dividing Equation (1) by Equation (2) leads to

$$\left(\frac{A}{A_o} \right) = 1/2 \left(\frac{\phi_p'}{\phi_p} + \frac{\phi_m'}{\phi_m} \right) \quad (3)$$

where ϕ_p is the unperturbed flux in the plexiglass. Equation (3) can be more conveniently expressed as

$$\left(\frac{A}{A_o} \right)^{\text{eff}} = \frac{2C_1 C_2 C_3}{C_1 + C_2 C_3} \quad (4)$$

where the following definitions have been made

$$C_1 \equiv \frac{\phi_m}{\phi_p}, \quad C_2 \equiv \frac{\phi_p}{\phi_p}, \quad \text{and} \quad C_3 \equiv \frac{\phi_m}{\phi_p}. \quad (5)$$

Equation (4) is the desired result, provided some method of obtaining the three flux ratios C_1 , C_2 , and C_3 is available.

For this experiment, the above three flux ratios were assumed independent of each other and obtained by using the Dunn approximation. The flux ratios C_1 and C_2 were assumed equivalent to the Dunn correction for full length pins surrounded, respectively, by an infinite medium of moderator and an infinite medium of plexiglass. The ratio C_3 was assumed equivalent to the Dunn correction for the 1/16-inch plexiglass in an infinite medium of moderator. All energy-averaged point thermal cross sections used in calculating these corrections were obtained from THERMOS.

Since the THERMOS mesh spacing and therefore the point cross sections did not coincide with the exact radial positions of any of the pins, the values of C_1 , C_2 , C_3 , and $(A_o/A)^{eff}$ were actually calculated at selected THERMOS radial mesh points. These values are tabulated for both the unpoisoned and the poisoned lattice in Table XVII below.

TABLE XVII

Copper Pin Correction Factors-THERMOS Outer Moderator MeshA. Unpoisoned Lattice

<u>R(cm)</u>	<u>C₁</u>	<u>C₂</u>	<u>C₃</u>	<u>(A_o/A)^{eff}</u>
3.0945	1.01342	1.01357	0.99866	1.01282
3.1935	1.01405	1.01420	0.99861	1.01342
3.4905	1.01487	1.01503	0.99854	1.01421
3.6885	1.01510	1.01527	0.99852	1.01443
3.7875	1.01517	1.01534	0.99852	1.01450
4.0845	1.01525	1.01543	0.99851	1.01458

B. Poisoned Lattice

3.0945	1.01205	1.01321	0.98967	1.00738
3.1935	1.01271	1.01389	0.98926	1.00783
3.4935	1.01338	1.01467	0.98872	1.00828
3.6885	1.01359	1.01490	0.98857	1.00842
3.7875	1.01366	1.01497	0.98853	1.00845
4.0845	1.01374	1.01506	0.98847	1.00852

Then the $(A_o/A)^{eff}$ values for the exact radial pin positions were obtained by graphic interpolation. These values are summarized below in Table XVIII, for both the unpoisoned and poisoned lattice.

TABLE XVIII

Correction Factors for Copper Pins in Outer Moderator

<u>Position</u> <u>R(cm)</u>	$(A_o/A)^{eff}$	
	<u>Unpoisoned</u>	<u>Poisoned</u>
3.17500	1.01333	1.00778
3.49250	1.01422	1.00828
3.64998	1.01440	1.00840
3.66268	1.01441	1.00841
3.81000	1.01451	1.00847
4.06400	1.01458	1.00852
4.15036	1.01459	1.00852

5.5 Central Cell End Effects

A systematic error in the interpretation of the results of a null reactivity measurement with certain types of lattices can be caused by the end effect. In heterogeneous systems such as this one, in which a significant fraction of the absorptions occur in non-fuel regions, the end-effect causes the PCTR null reactivity condition to overpredict the test cell's just critical amount of poison. This is caused by the following:

Removing the central cell causes a net increase in flux at the buffer-void interfaces. This results in a larger absorption than production increase in the perturbed portion of the buffer region, relative to the cell in condition. This causes the cell worth and therefore the correct amount of poison to be overestimated.

Under these circumstances, the PCTR null reactivity condition is met not because the test lattice is poisoned correctly, but because the net reactivity increase gained by removing the overpoisoned central cell is exactly counterbalanced by the net loss of reactivity caused by the end effect. The net result is a measured β' that is too small and a k_{∞} for the unpoisoned test lattice that is too large. The magnitude of this affect depends on the size of the removable test cell. There are two methods of directly measuring this end effect; one requires a large number of additional activation and fission rate measurements in the buffer region and the other requires the fabrication of additional central cell assemblies of at least two different lengths. Neither of these methods was used for this experiment because of cost considerations. The systematic error in the measured k_{∞} caused by the end affect in this experiment is estimated to be on the order of + 4 mk. The basis of this estimate is discussed further in the theory-experiment correlation section

6. THEORY-EXPERIMENT CORRELATION

In this last section, the theory-experiment correlation of k_{∞} , pin and foil ^{63}Cu activation distributions, and thermal utilizations are presented which, as a whole, supports both the overall accuracy of the experiment data and the adequacy of the methods used in the analysis of this experiment. The discrete ordinate transport theory codes, ANISN⁽¹²⁾ and DOT⁽¹³⁾, were used in this correlation with the following choice of "options":

1. Linear anisotropic scattering
2. S_4 angular quadrature
3. Fission engenvalue
4. Zero leakage
5. "White" radial boundary condition.

6.1 Comparison of Measured k_{∞} with Transport Theory

The comparison between the measured and the one and two dimensional transport theory infinite multiplication values is summarized in Table XIX.

TABLE XIX
Measured and Calculated k_{∞} For A Rod In
Tube Assembly In A 3.1 Inch Triangular Pitch Water Lattice

<u>Nominal Condition</u>	<u>wppm Boron</u>	<u>k_{∞}</u>		
		<u>Poisoned Technique</u>	<u>ID Transport Theory</u>	<u>2D Transport Theory</u>
Unpoisoned	0	$1.1063 \pm .0084$	1.0926	$1.094 \pm .003$
At Measured Null Reactivity Boron Concentration	550 ± 12	1.0	0.995	$0.996 \pm .002$

Taking the measured value as it stands, the agreement between theory and experiment is only fair. However, an estimated value of 0.996 ± 0.002 for the end effect correction factor could be obtained directly from the value of the poisoned lattice k_{∞} calculated using two dimensional transport theory. If the measured k_{∞} of the unpoisoned lattice is multiplied by this correction factor, a value of 1.1019 ± 0.0087 is obtained, which brings the calculated and measured values into agreement within the quoted uncertainty. Assuming this estimate is accurate, then the proper boron concentration for a just critical infinite lattice would be about 528 ± 12 wppm.

6.2 Comparison of THERMOS with Copper Foil and Pin Sub-Cadmium Activation Measurements

The precision of the 0.036 inch diameter by 0.25 inch long copper pin measurements in the outer moderator of this hexagonal cell provides an excellent opportunity for assessing the results of calculations using a cylindrical geometric model. The complete set of this pin data (corrected to $Z = -9.6012\text{cm}$) is summarized in Table XX. The THERMOS results were normalized (best fit) to the following measured sub-cadmium values of two 0.0625 inch diameter by 0.5 inch long copper pins (also corrected to $Z = -9.6012\text{cm}$) in the target.

<u>R(cm)</u>	$\text{SA}_{\text{Sub Cd}}^{63}$	
	<u>Unpoisoned</u>	<u>Poisoned</u>
0.000	1.01711	0.57626
0.683	1.09512	0.62951

The THERMOS normalization to the larger diameter pins was chosen to keep the normalization independent from both the smaller diameter pin data and the 0.010 inch thick sector foil data and also to accentuate any deviations between theory and experiment in the outer moderator. The axial position of $Z = -9.6012\text{cm}$ was chosen in an attempt to keep the comparison as clean as possible; i.e., 1) the axial perturbations caused by the target aluminum end- and mid-caps are essentially damped out at this position, 2) the inner and outer moderator sector foils were irradiated at this position, and 3) since the smaller diameter pins were irradiated at the physically summetric position of $Z = \pm 9.6012\text{cm}$, the magnitude of the pin data axial correction to this position was very small (less than 1%). The comparison of THERMOS

TABLE XX

Corrected Copper Pin Activities in Outer ModeratorA. Unpoisoned Lattice (Z=-9.6012cm)

<u>R(cm)</u>	<u>θ</u>	<u>SA_B^{63}</u>	<u>SA_{Cd}^{63}</u>	<u>$SA_{Sub\ Cd}^{63}$</u>	<u>CdR^{63}</u>	<u>$SA_{1/v}^{63}$</u>
3.17500	30°	4.12106	0.54104	3.58002	7.6169	3.88008
3.66268	30°	5.82782	0.55379	5.27403	10.5235	5.58116
4.15036	30°	6.49238	0.56801	5.92437	11.4300	6.23939
3.17500	17°46'	3.94894	0.55119	3.39775	7.1644	3.70344
3.64998	17°46'	5.58380	0.57231	5.01149	9.7566	5.32889
4.06400	17°46'	6.01699	0.57561	5.44138	10.4532	5.76061
3.17500	0°	3.82280	0.54741	3.27539	6.9834	3.57898
3.49250	0°	4.92602	0.56442	4.36160	8.7276	4.67463
3.81000	0°	5.32854	0.56864	4.75990	9.3707	5.07527

B. Poisoned Lattice (Z=-9.6012cm)

3.17500	30°	2.32750	0.33472	1.99278	6.9536	2.17842
3.66268	30°	3.32474	0.34149	2.98325	9.7360	3.17264
4.15036	30°	3.79399	0.34701	3.44698	10.9334	3.63943
3.17500	17°46'	2.27275	0.34279	1.92996	6.6302	2.12007
3.64998	17°46'	3.20768	0.35056	2.85712	9.1502	3.05154
4.06400	17°46'	3.53100	0.35386	3.17714	9.9785	3.37339
3.17500	0°	2.14913	0.33375	1.81538	6.4393	2.00048
3.49250	0°	2.72119	0.33925	2.38194	8.0212	2.57009
3.81000	0°	2.95329	0.34823	2.60506	8.4809	2.79819

The origin of the angle θ is on the chord connecting the center of the removable cell to the center of any adjacent cell.

with the copper pin and sector foil data is graphically presented in Figure 13 and 14 for both the unpoisoned and poisoned lattice.

In general THERMOS agrees quite well with the measured data. The radial distribution of the foil averages is slightly flatter than that of the calculated averages. This may be due in part to the use of the Dunn approximation in correcting for the foil perturbations, since it has a tendency to somewhat underpredict both the peaking and dipping of the foil flux with respect to the surrounding media; and in part to the cylindrical boundary assumed in the calculations. THERMOS overpredicts the outer moderator to fuel thermal neutron density ratio by about $4 \pm 1\%$ compared to the foil data for both lattices. This assumes no uncertainty in the foil perturbation corrections and no uncertainty in the boron concentration. If the pin data and THERMOS results are assumed to be identical in the fuel region, then the calculated outer moderator to fuel neutron density ratio is over predicted by 1.4% for the unpoisoned lattice and under predicted by 1.3% for the poisoned lattice. The uncertainty in these errors, however, is at least as large as the errors themselves, due to the simple trapezoidal angular integration followed by a Simpson's radial integration used to obtain the pin averages. Therefore, with respect to the pin average and the above index of adequacy, the use of the isotropically-reflecting, equivalent cylindrical boundary gives very good results for both lattices. Although relatively unimportant to the k_{∞} measurement, the use of the pseudo boundary in the calculations does result in a significant under prediction of the relative neutron density in the neighborhood of the actual cell boundary for both of these lattices.

FIGURE 13. RADIAL SUB-CADMIUM ^{63}Cu TRAVERSE AT $Z = -9.6012$ cm UNPOISONED LATTICE

FIGURE 14. RADIAL SUB-CADMIUM ^{63}Cu TRAVERSE AT $z = -9.6012$ cm
POISONED LATTICE

6.3 Comparison of Measured Cell Thermal Utilizations with the One-Dimensional THERMOS and ANISN Results

The relative thermal absorption rate density is obtained in the same manner as the $1/v$ rates described in Section 4.8 except that $SA_{\text{Sub Cd}}^{63}$ is used instead of $SA_{1/v}^{63}$. These "measured" values and the quantities necessary for their determination are tabulated in Table XXI for both lattices. The resulting thermal utilization for all cell regions and the associated ANISN and THERMOS values are compared in Table XXII. The agreement in general is quite good in spite of the fact that the aluminum end- and mid-caps were either smeared into the target (THERMOS) or neglected completely (ANISN) to obtain the theoretical results.

TABLE XXI

Experimental Relative Thermal Absorption RatesA. Unpoisoned Lattice

Region	$\hat{\Sigma}_a$ (cm ⁻¹)	SA ⁶³ _{Sub Cd} ± (%)	Volume (cm ³)	Relative Thermal Absorptions ^a
Target	0.548311	1.21753(0.587)	336.5063	852.8043 ± 5.0066
Target Al Clad	0.014164	1.52164(4.412)	142.5877	11.6662 ± 0.5147
Target Zr Clad	0.007990	1.58864(4.412)	46.7417	2.2523 ± 0.0994
Inner Moderator	0.022184	1.98918(0.509)	354.9636	59.4631 ± 0.3027
Fuel Inner Zr Clad	0.007990	1.67951(4.412)	54.1227	2.7571 ± 0.1216
Fuel	0.769873	1.79281(0.481)	697.9688	3657.1182 ± 17.5907
Fuel Outer Zr Clad	0.007990	2.32278(4.412)	95.9603	6.7608 ± 0.2983
Outer Moderator	0.022184	4.45061(0.295)	1469.7742	550.8833 ± 1.6251
Target Al End Caps	0.012296	1.85570(5.000)	14.2941	1.2382 ± 0.0619
				5144.9435 ± 18.3741

B. Poisoned^b Lattice

Target	0.548311	0.70706(0.152)	336.5063	495.2417 ± 0.7528
Target Al Clad	0.014164	0.99300(1.320)	142.5877	7.6132 ± 0.1005
Target Zr Clad	0.007990	1.03267(1.320)	46.7417	1.4641 ± 0.0193
Inner Moderator Water	0.022184	1.13353(0.470)	354.9636	33.8849 ± 0.1593
Inner Moderator Boron	0.023257	1.13353(2.232) ^b	354.9636	35.5239 ± 0.7929
Fuel Inner Zr Clad	0.007990	1.02109(1.320)	54.1227	1.6763 ± 0.0221
Fuel	0.768417	1.03470(0.354)	697.9688	2106.6726 ± 7.4576
Fuel Outer Zr Clad	0.007990	1.44129(1.320)	95.9603	4.1951 ± 0.0554
Outer Moderator Water	0.022184	2.41245(0.247)	1469.7742	298.6059 ± 0.7376
Outer Moderator Boron	.023257	2.41245(2.196) ^b	1469.7742	313.0489 ± 6.8746
Target Al End Caps	.012296	1.08667(0.215)	14.29407	0.7250 ± 0.0016
				3298.6616 ± 10.2301

^aRelative to the ⁶³Cu absorption rate density of natural copper in the thermal column.

^b550 ± 12 wppm boron in moderator.

TABLE XXII
Experimental and Calculated Thermal Utilizations

A. Unpoisoned Lattice

Region	Thermal Utilizations ^b		
	Experiment	THERMOS	ANISN
Target	0.16576 ± .00114	0.16431 ^a	0.16305
Target Al Clad	0.00227 ± .00010	0.00258	0.00237
Target Zr Clad	0.00044 ± .00002	0.00050	0.00046
Inner Moderator	0.01156 ± .00007	0.01170	0.01108
Fuel Inner Zr Clad	0.00054 ± .00002	0.00058	0.00057
Fuel	0.71082 ± .00425	0.70887	0.71101
Fuel Outer Zr Clad	0.00131 ± .00006	0.00145	0.00139
Outer Moderator	0.10707 ± .00050	0.11002	0.11007
Target Al End Caps	0.00024 ± .00001	-	-

B. Poisoned Lattice

Target	0.14014 ± .00052	0.14890 ^a	0.14794
Target Al Clad	0.00231 ± .00003	0.00233	0.00214
Target Zr Clad	0.00044 ± .00001	0.00045	0.00041
Inner Moderator	0.02104 ± .00025	0.02157	0.02043
Fuel Inner Zr Clad	0.00041 ± .00001	0.00042	0.00051
Fuel	0.63865 ± .00301	0.62905	0.63134
Fuel Outer Zr Clad	0.00127 ± .00002	0.00128	0.00123
Outer Moderator	0.18543 ± .00217	0.19591	0.19601
Target Al End Caps	0.00022 ± .00000	-	-

^aTarget aluminum end caps included with correspondingly reduced density target.

^bFull density target - target end caps neglected.

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