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PCTR MEASUREMENT OF THE REACTIVITY EFFECTS
OF 0.8% ENRICHED URANIUM FUEL IN A
GRAPHITE MODERATED LATTICE WITH VARIOUS
AMOUNTS OF WATER COOLANT AND FLOODING

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INTRODUCTION

Neutronic parameters with various water coolant and flooding conditions in a 7-1/2 inch square pitch graphite lattice containing 0.8% enriched uranium metal fuel have been measured in the Physics Constants Test Reactor.

This report describes the techniques and the experimental measurements necessary to derive the infinite medium neutron multiplication factor in four cases; namely, two different simulated flooding conditions, normal cell conditions, and the dry cell. Finally, the neutronic parameters of an actual water flooded cell were measured and some preliminary results are derived which provide a comparison of the effects of actual water flooding with simulated flooding. All measurements were made at room temperature.

SUMMARY

The measurement of k_{∞} in the experimental analysis followed two techniques; namely, the null reactivity measurement technique⁽¹⁾ and the excess neutron adjoint weighted cross section technique⁽²⁾. The results are listed in Table I for all the matched cell conditions.

Several perturbation measurements were taken which differ slightly from the basic cell conditions listed in Table I. For the perturbation results, measurements were taken on the central test cell; however, the buffers were at slightly different conditions. These measurements are helpful in estimating the reactivity effects due to partial changes in a reactor lattice and are useful for experimental verification of calculational

TABLE I. Lattice Parameters Determined From PCTR Measurements
(0.8 wt% Enriched Uranium Fuel - 7.5 Inch Lattice Pitch)

Condition	Thermal Util. Air Atmosphere	k_{∞} (Null React. Measurement)	k_{∞} (Non-Poison Measurement)*
Normal coolant (water in process channel)	0.933 ± 0.011	0.9853 ± 0.0035	0.9848 ± 0.0035
Process channel flooding (simulated with polyethylene wrap around process tube)	0.888 ± 0.001	1.0065 ± 0.0033	1.0071 ± 0.0034
Process channel and gas vent flooding (simulated with polyethylene wrap around process tube and lucite in gas vents)	0.852 ± 0.010	1.0014 ± 0.0038	1.0003 ± 0.0038
Actual water flooding (center cell in aluminum tank filled with water - buffer cells simulated flooding as above)	0.806 ± 0.010	0.9672 ± 0.0030	0.9693 ± 0.0030
Dry Cells	----	----	0.9109 ± 0.0036

* Excess neutron production adjoint weighted cross section measurement⁽²⁾.

techniques. The results of these measurements, listed in Table II are in terms of the mass of copper necessary to achieve unit multiplication.

TABLE II. *Measured Mass of Copper Necessary To Achieve Unit Multiplication*

	<u>Mass of Copper (grams)</u>
Normal coolant case with water in process tube	- 54.8 $\pm$ 0.7
Water in process tube and 295 cc water in center cell moderator (buffer cells with normal coolant and no water in graphite	+ 152 $\pm$ 4
Water in process tube and polyethylene wrap around process tube (buffer cells with normal coolant and no polyethylene wrap)	+ 450 $\pm$ 5
Water in process tube and simulated flooding in hole bar with polyethylene wrap around process tube (all cells)	+ 63.0 $\pm$ 0.8
Water in process tube and simulated flooding in hole bar with polyethylene wrap around process tube and simulated flooding in gas vents with lucite (all cells)	+ 46 $\pm$ 4
All cells dry	- 368 $\pm$ 7
One cell dry - buffers with normal coolant	- 211 $\pm$ 5
Water flooded center cell and simulated flooding in all buffer cells	- 97 $\pm$ 2

DESCRIPTION OF THE EXPERIMENT

PCTR Test Lattice

The test lattice was constructed with specially cut graphite moderator blocks arranged on 7.5 inch centers and stacked in a 5 x 5 array in the test cavity of the Physics Constants Test Reactor (PCTR). A photograph of this arrangement is shown in Figure 1 and depicts the driver arrangement necessary to achieve critical with the test lattice in a normal condition, that is, with coolant in the process tube and gas vents containing air.

FIGURE 1. PCTR Test Lattice With Moderator
Used for Various Flooding Measure
ments

Individual Cell Parameters

The test cells were specifically designed to permit the addition of simulated flooding materials at strategic locations. The hole bar containing a 3.0 inch O.D. hole for the process tube was undercut to make gas vents which would normally be used to dry the lattice in an operating reactor but which would be flooded in the event of a process tube rupture.

Likewise, the process tube channel in the hole bar was enlarged sufficiently to permit the addition of a flooding simulator between the process tube and the graphite. These dimensions are better illustrated in Figure 2 which depicts the front face plane of an individual cell in the test lattice.

The 7.5 inch lattice block was undercut 0.020" in specific locations for the addition of copper strip which are used as neutron absorber in the experimental measurements with the poison technique. In this experiment the strips were 2.5 inches in width and therefore two cuts were made on each face of a test cell. These cuts are not depicted in Figure 2.

Cell Components

The fuel was metallic uranium containing 0.8 wt% U^{235} enrichment, aluminum cladding, and contained in a zirconium process tube.

Water was always used as coolant in the process tube because the tube could be sealed; however, polyethylene was wrapped around the process tube to simulate process channel flooding and lucite was placed in the gas vents to simulate gas vent flooding. Figure 3 shows the arrangement of polyethylene and lucite in the central test cell.

The fuel element is nominally 8.870 inches in length and this includes a 0.230 inch thick end cap at each end. Therefore the center test cell used for the reactivity measurements was two complete fuel elements including their end caps. The front and rear buffers were each a single fuel element which was

FIGURE 2. Overbore Cell Dimensions (Front Face Plane)

sufficient to achieve a matched neutron incident spectrum on the center test cell and not exceed the 37.5 inch depth of the PCTR test cavity.

This fuel was chosen because of its larger diameter and correspondingly higher fuel to moderator ratio region.

Details of the center test cell are listed in Table III and Table IV for normal coolant conditions and simulated flooding conditions, respectively.

Isotopic Analysis Data

It is standard practice to obtain an isotopic analysis of the fuel used in an experiment in order that exact absorption rates may be derived from the data. The results of this analysis are listed in Table V.

EXPERIMENTAL TECHNIQUE

The PCTR Method of Determining k_{∞}

The general techniques for determining the infinite medium neutron multiplication factor (k_{∞}) for test lattices in the Physical Constants Test Reactor (PCTR) are discussed in Reference 5. A summary of this method is included here to make the data which follows more meaningful. Basically, the PCTR experiment follows these procedures:

Spectrum matching which is the adjustment of the neutron energy spectrum so that it is identical to an infinite array of test cells.

Neutron absorber measurements to determine the amount of neutron absorber (copper) required to achieve unit multiplication in the test cell.

Measurement of the relative reaction rates of the components of the test cell in both the lattice reduced to unit multiplication with copper and the lattice without the copper added.

TABLE 111. Geometry and Parameters of Center Cell Containing Water Coolant

Region	Isotope	Radius (cm)	Density gm/cm ³	Mass (gm)	Volume cm ³
Fuel		1.102	17.570 ⁽²⁾	3 020.463	171.909
	235 U			24.164	162.994
	238 U		0.140 ⁽²⁾	2 996.300	
	Al (caps)			24.071	8.915
Fuel Clad	Aluminum	1.214	2.70	99.144	36.720
Water		1.567	0.992 ⁽³⁾	137.809	138.967
	Hydrogen			15.435	137.809
	Oxygen		0.0225	122.374	
	Al (supports)			3.127	1.158
Fuel Clad	Aluminum	1.681	2.70	141.525	52.417
Fuel		3.000	17.570 ⁽²⁾	15 356.534	874.016
	235 U			122.852	828.705
	238 U		0.140 ⁽³⁾	15 233.682	
	Al (caps)			122.340	45.311
Fuel Clad	Aluminum	3.113	2.70	264.020	97.785
Water		3.368	0.992 ⁽³⁾	231.620	233.068
	Hydrogen			25.941	
	Oxygen		0.0225	205.679	
	Al (supports)			3.907	1.448
Process Tube	Zirconium	3.482	6.40	707.481	110.544
Air		3.810	1.293 x 10 ⁻³	0.044	338.580
	Nitrogen			0.034	
	Oxygen			0.010	
Moderator		5.240 ⁽¹⁾	1.770	3 242.250	1 831.999
	Carbon			3 242.250	
	Nitrogen			0.360	
	Oxygen			0.109	
Air		5.418 ⁽¹⁾	1.293 x 10 ⁻³	0.349	269.564
	Nitrogen			0.268	
	Oxygen			0.081	
Moderator		10.747 ⁽¹⁾	1.627	19 836.900	12 194.448
	Carbon			19 836.900	
	Nitrogen			3.473	
	Oxygen			1.049	

(1) Cylindricized radius.

(2) Reduced density because of aluminum end caps.

(3) Reduced density because of aluminum supports.

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TABLE IV. Geometry and Parameters of Center Cell With Simulated Flooding Conditions

Region	Isotope	Radius (cm)	Density gm/cm ³	Mass (gm)	Volume (cm ³)
Fuel	²³⁵ U	1.102	17.570 ⁽²⁾	3 020.463	171.909
	²³⁸ U			24.164	
	Al (caps)		0.140 ⁽²⁾	2 996.300	162.994
Fuel Clad		1.214		24.071	8.915
	Aluminum		2.70	99.144	36.720
Water		1.567	0.992 ⁽³⁾	137.809	138.967
	Hydrogen			15.435	
	Oxygen			122.734	137.809
Fuel Clad	Al (supports)	1.681	0.0225	3.127	1.158
	Aluminum		2.70	141.525	52.417
Fuel		3.000	17.570 ⁽²⁾	15 356.534	874.016
	²³⁵ U			122.582	828.705
	²³⁸ U			15 233.682	
Fuel Clad	Al (caps)	3.113	0.140 ⁽²⁾	122.340	45.311
	Aluminum		2.70	264.020	97.785
Water		3.368	0.992 ⁽³⁾	231.620	233.068
	Hydrogen			25.941	
	Oxygen			205.679	
Process Tube	Al (support)	3.482		3.907	
	Zirconium		6.40	707.481	110.544
Polyethylene & Air		3.810		250.714	338.580
	Carbon			213.902	269.564
	Hydrogen			35.984	
	Nitrogen			0.636	69.016
Moderator	Oxygen	5.240 ⁽¹⁾	1.770	0.192	
	Carbon			3 242.250	1 831.999
	Nitrogen			3 242.250	
Lucite	Oxygen	5.418 ⁽¹⁾		0.360	
	Carbon			0.109	
	Hydrogen			295.160	269.564
	Oxygen			177.096	
Moderator		10.747 ⁽¹⁾	1.627	23.613	
	Carbon			94.451	
	Nitrogen			19 836.900	12 194.448
	Oxygen			19 836.900	
				3.473	
				1.049	

(1) Cylindricized radius.

(2) Reduced density because of aluminum end caps.

(3) Reduced density because of aluminum supports.

TABLE V. Isotopic Analysis Data of Fuel^(a)

Isotope	at%
²³⁴ U	0.0070 ± 1
²³⁵ U	0.8056 ± 30
²³⁶ U	0.0405 ± 3
²³⁸ U	99.1469

(a) Reported by C. R. Lagergren.

effect on the reactor as on an empty cavity. In a properly poisoned cell the neutron absorptions balance the neutron productions. The central test cell which was the test cell for the null reactivity measurements is shown being removed from the PCTR test lattice in Figure 4. Short end buffer cells enclose the central cell along the long axis. Slots are provided in the lattice for the insertion of copper poison strips at the cell boundaries.

A reactivity series was completed for each loading for which the cadmium ratio of gold foils was measured. The basic technique has been simplified to the equation below:

$$M_o = \frac{\rho \text{ cell in} - \rho \text{ cell out}}{\text{Units of reactivity per gram of absorber}} + M_{\text{cu}}^{\text{boundary}}$$

where $M_{\text{cu}}^{\text{boundary}}$ = Mass of copper on the cell boundaries;

$\rho \text{ cell in}$ = PCTR reactivity with cell in;

$\rho \text{ cell out}$ = PCTR reactivity with cell out,
corrected to exclude nitrogen effects.

It can be readily seen that the reactivity worth of the center test cell and of the absorber will change as the neutron spectrum changes. By making sufficient changes in the flux modifiers and taking adequate reactivity measurements, it is possible to extrapolate to the exact neutron absorber requirements for the matched spectrum conditions.

The differences in the cadmium ratio values and the respective measured masses of neutron absorber are listed in Table VI for all the different test lattices of this experiment.

Least Squares Analysis of M_o Quantities

The data listed in Table VI was analyzed via a least squares derivation of the linear relationship between the quantity (CTR-RD) and the measured M_o for each cell condition. The results of this analysis are shown in Figures 5, 6 and 7 which illustrate the

FIGURE 3. Center Test Cell With Simulated Process Channel Flooding (Polyethlene) and Simulated Gas Vent Flooding (Lucite)

Measurement of the neutron leakage ratio from the test cell in order to determine the value of k_{∞} from the excess neutron adjoint weighted cross section.

Spectrum Matching

The neutron energy distribution was inferred by measuring cadmium ratios of 0.005 inch thick gold foils and comparing the cadmium ratio in the center test cell with the values obtained at an equivalent location in a buffer region. The gold, when covered with cadmium, is activated almost entirely by neutrons in a narrow energy region around 4.9 ev. The large number of foils necessary for this measurement usually have slightly different thicknesses and therefore the cadmium ratios must be corrected to a standard foil thickness using experimental data published by R. A. Bennett.⁽⁶⁾

A weighted average ($\overline{RD}$) of the cadmium ratio of the buffer cell locations was computed for comparison with the cadmium ratio ($\overline{CTR}$) of the foils irradiated in the center cell. The weighting used was the inverse of the linear distance, center to center, from a buffer cell to the center cell. The specific criteria for flux match is defined as the equivalence of $\overline{CTR}$ and $\overline{RD}$.

It is impractical to achieve an exact equivalence between the buffer cells and center test cell; however, it is important to make several driver and flux modifier changes in order to determine the sensitivity of the measured mass of neutron absorber (M_0) necessary to achieve unit neutron multiplication with respect to changes in the neutron spectrum. This is usually a function of the difference between the average cadmium ratios measured in the buffer cells and center cell. Therefore at each loading change, a series of reactivities are measured, called null reactivity measurements, to determine the quantity M_0 .

Null Reactivity Measurements

The null reactivity technique depends on the observation that a properly poisoned cell will have the same reactivity

FIGURE 4. Central Test Cell Being Removed
from PCTR Test Lattice

FIGURE 5. Results of Least Squares Analysis of Reactivity and Cadmium Ratio Data with Normal Coolant Conditions

FIGURE 6. Graphic Results of Least Squares Analysis of Reactivity Cadmium Ratio Data With Simulated Flooding Conditions Around Process Tube

FIGURE 7. Graphic Results of Least Squares Analysis of Reactivity and Cadmium Ratio Data with Simulated Flooding Conditions Around Process Tube and in Gas Vents

TABLE VI. Results of Cadmium Ratio Measurements and
Respective Neutron Absorber Requirements

Experiment No.	Cell Conditions	Difference Between Average Cadmium Ratio In Center Cell and Weighted Cadmium Ratio of Buffer Cells(CTR-RD)	(M _O) (grams)
6704.1	Normal coolant	- 0.027	- 55.6 ± 3.5
6704.2	Normal coolant	+ 0.016	- 55.1 ± 3.5
6704.3	Normal coolant	+ 0.043	- 51.6 ± 4.4
6704.4	Simulated flooding around process tube with poly- ethylene wrap	- 0.025	+ 63.2 ± 3.6
6704.5	Simulated flooding around process tube with poly- ethylene wrap	- 0.085	+ 65.0 ± 6.3
6704.6	Simulated flooding around process tube with poly- ethylene wrap	- 0.025	+ 64.3 ± 3.6
6704.7	Simulated hole bar flooding plus lucite in gas vents	- 0.048	+ 47.4 ± 2.6
6704.8	Simulated hole bar flooding plus lucite in gas vents	- 0.104	+ 41.2 ± 3.0
6704.9	Simulated hole bar flooding plus lucite in gas vents	+ 0.104	+ 48.4 ± 2.9
6704.10	All cells dry	+ 0.037	- 366.0 ± 7.5
6704.11	All cells dry	- 0.079	- 372.3 ± 7.7

M_O = Measured mass of copper necessary to achieve unit multiplication in test cell.

linear extrapolations of the inferred mass of copper (M_O) to the matched cell conditions. The results are summarized in Table VII.

TABLE VII. *Summary of Inferred Mass of Copper and Corrected 1/v Mass*

<u>Cell Conditions</u>	<u>Inferred Mass (M_O) (grams of copper)</u>	<u>Corrected 1/v Mass (gram of copper)</u>
Normal coolant conditions	- 54.8 $\pm$ 0.7	- 58.8
Simulated flooding around process tube	+ 63.0 $\pm$ 0.8	+ 66.3
Simulated flooding around process tube and in gas vents	+ 46.0 $\pm$ 3.4	+ 48
Dry cell conditions	-368.0 $\pm$ 7	-383

The results of these measurements indicate that the mass of copper (M_O) for each condition was not found to be very sensitive to spectrum changes and therefore only a few measurements were necessary for each condition. The inferred absorber mass for the dry cell conditions was interpolated between two measurement values because the neutron spectrum in the test lattice could not be altered sufficiently to significantly change the measured mass of copper neutron absorber.

The inferred mass must be corrected to a value for a 1/v absorber in order to be used later to calculate 1/v reaction rates. These corrected values are listed in Table VI and the corrections are explained in Appendix A.

RELATIVE REACTION RATE AND K_{∞} DETERMINED BY
NULL REACTIVITY TECHNIQUE

Foil Data

Relative reaction rates of the test cell components are determined from foil activation measurements. The energy dependence of the reaction rates are determined from cadmium ratios.

Once the gold cadmium ratio information has indicated that the test cells have the proper energy distribution, copper foils (0.010 inch thick) and pins (0.036 inches O.D.) were strategically placed in the graphite, fuel, and coolant channels. Bare and cadmium covered foils and pins were activated in separate irradiations and normalization between irradiations was accomplished by placing monitor foils in an external thermal⁽⁷⁾

Foil and pin locations as illustrated in Figure 8 are sufficiently provided so that radial and axial plots of the relative reaction rates can be determined throughout the center test cell. A photograph of the relative center test cell and all the associated foil holders which were used in this experiment to derive the relative reaction rates is shown in Figure 9.

Special sector and quadrant foils were made to integrate the neutron reaction rate over the area of the fuel rod and fuel tube, respectively. In order to obtain spatial detail of the reaction rate integrals, a copper sector foil and quadrant foil from the disc foil were dissected into several annular regions after the irradiation. These foils were all counted separately and yielded a histogram of specific activities relative to the monitor foil in the external thermal column.

Cadmium dishes in the separable fuel element were designed so that they displaced the aluminum cladding in order to allow the inside dimensions of the dish to be identical to the fuel

FIGURE 8. Front Face Plan of Center Test Cell Showing Foil and Pin Locations for Radial Flux Traverse

FIGURE 9 Center Test Cell With Associated Foil Holders and Separable Fuel Element

core dimensions. Foils placed inside the cadmium dish, one mil aluminum fission product catcher foils on their surfaces, were between two wafers of fuel core material, also inside the cadmium dish. Bare foils, having one mil aluminum fission product catcher foils on their surfaces, were placed in special holders machined from the core material.

The specific activation of the copper foils and pins placed in the graphite relative to the foil and pins in the thermal column are presented in Table VIII. The activities were 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 variations, and residual activity. The foil activities are listed in Table VII as they were received from APDAC in order to provide a record of this unmodified foil and pin data. Further corrections must be applied for the geometrical differences if the foils and pins as well as corrections for changes in the flux due to the presence of the foil. A discussion of these corrections follow as well as a plot of the corrected activities.

The axial traverse data remained relatively constant throughout the experiment. Axial traverses were taken with 0.010 inch thick copper square foils (0.443 inch) by placing the foils along the fuel cladding, process tube surface and at the cell boundary. In order to give some idea of these distributions, this data has been plotted in Figure 10 for the normal coolant case. This is unmodified data, as received from the revised APDAC-I computer code calculations.

Corrections to Foil and Pin Data (See Appendix A)

Several corrections must be applied to the foil and pin data after the APDAC calculated corrections. A geometry correction for the pin data is applied by multiplying the activities of the pins by the ratio of the activities of a 0.010 inch thick copper

TABLE VIII. Copper Foil and Pin Activities - Radial Traverses

Foil or Pin Designator	Radius (Inches)	Normal Coolant Conditions		Simulated Flooding Around Process Tube		Simulated Flooding Around Process Tube And In Gas Vent	
		Bare	Cd. Covered	Bare	Cd. Covered	Bare	Cd. Covered
Cell Boundary							
r ₁	3.365	4.37274	.44897	6.22321	.43714	7.55453	.44178
r ₂	2.815	4.20085	.45782	5.92660	.45776	7.36888	.43356
r ₃	2.365	4.15917	.44820	5.62789	.47786	7.34579	.44669
		3.89918	.44490	5.71491	.45813	7.22682	.42686
Gas Vent							
r ₄	1.737	3.78000	--	5.75000	--	6.97682	--
r ₅	1.790	3.63501	.42909	5.44175	.43580	6.48388	.41500
		3.65445	.42676	5.37160	.42800	6.51340	.41164
Gas Vent							
r ₆	2.400	3.77000	--	5.67000	--	6.85090	--
r ₇	2.900	3.96327	.44214	5.77688	.44969	7.16967	.42151
r ₈	3.400	4.12810	.45202	5.47630	.44692	7.37127	.43439
		4.23135	.45467	5.92601	.46271	7.44844	.43306
Cell Boundary							
r ₉	1.790	4.33654	.44238	6.18959	.43293	7.52714	.43356
		3.57610	.42325	5.16781	.42927	6.35445	.41742
Gas Vent							
r ₁₀	2.400	3.72000	--	5.61000	--	6.81319	--
r ₁₁	2.900	3.88875	.44912	4.36195	.46085	7.03206	.43601
r ₁₂	3.400	4.08476	.45204	5.76277	.46853	7.27918	.44560
		4.14953	.44917	5.94002	.44969	7.19741	.44752
Cell Boundary							
r ₁₃	1.808	4.29363	.43830	6.11991	.43256	7.33230	.43021
r ₁₄	3.500	3.54350	.42114	5.31449	.43218	6.27138	.41749
r ₁₅	3.000	3.91554	.43990	5.72565	.44353	6.91563	.42324
r ₁₆	3.500	4.10148	.45146	5.79690	.45441	7.03940	.45771
		4.23159	.45029	5.90619	.45418	7.30216	.43804
Cell Boundary							
		4.28901	.43670	6.16791	.43513	7.41092	.43500
Disc A (Avg)							
Quadrants 1		--	.38160	--	.35283	2.01917	--
2		1.58006	--	1.90697	--	1.86670	--
3		1.57500	--	2.01063	--	1.88433	--
4		1.57556	--	2.00156	--	2.06474	--
		Dissected	--	Dissected	--	Dissected	--
Sectors B							
C		2.04567	.41738	2.39722	.37847	2.81196	.38509
D		Dissected	Dissected	2.40704	.38102	2.69971	.40245
E		1.96921	.40845	2.40822	.38716	2.75335	.39373
		2.03479	.41285	2.35374	.38098	2.74157	.40017
Fuel Clad Boundary							
Inner	0.434	--	--	--	--	--	--
Outer	1.181	2.91214	.40551	3.41318	--	4.50248	--
Process Tube Boundary	1.336	3.36545	.39500	5.55856	.40000	6.10212	.40948

FIGURE 10. Axial Traverse Data of Bare Foils on Outer Cell With Normal Coolant Conditions

foil and pin irradiated simultaneously in the thermal column during each irradiation.

It is also necessary to correct for the change in the flux in any region due to the foil's presence in the same region. This correction follows a method derived by F. E. Dunn (KAPL)⁽⁹⁾ and uses the equation shown below:

$$\frac{A_{\text{foil}} - A_0}{A_{\text{foil}}} = t (\Sigma_{\text{medium}} - \Sigma_{\text{foil}}) \ln L/t$$

where A_{foil} = Activation of foil as measured in medium
 A_0 = Activation that would occur if the flux in the foil were the same as the flux in the medium
 t = Thickness of foil (cm.)
 Σ_{medium} = Macroscopic absorption cross section of medium
 Σ_{foil} = Macroscopic absorption cross section of foil
 L = Diameter of foil (cm.)

The measured spatial distribution of the relative reaction rates in copper-63, SA^{63} , must also be corrected for non-1/v absorption reactions. These non-1/v corrections were inferred from copper-63 cadmium ratio measurements and resonance integral data⁽⁶⁾.

$$SA_{1/v}^{63} (R) = SA_{\text{total}}^{63} (R) - SA_{\text{epi-cd}}^{63} \frac{RI_{\text{ex.}}}{RI_{\text{epi-cd.}}}$$

where RI_{ex} = effective excess resonance integral for copper-63 in a 0.010 inch thick foil, 1.631 barns
 $RI_{\text{epi-cd}}$ = effective total epi-cd. resonance integral for copper-63 in a 0.010 inch thick foil, 3.420 barns

Comparison of Measured Foil Activities With THERMOS Calculations

The THERMOS⁽¹⁰⁾ code was used to derive the radial flux patterns for each type cell condition under consideration in this experiment. The theoretical patterns were then plotted with the radial patterns derived from the experimental irradiations and with each case normalized to unity at the inner fuel rod. These graphs are presented in Figures 11, 12 and 13.

Neutron Cross Sections

Thermal neutron spectrum averaged microscopic cross section values, calculated by transport theory, were obtained from the computer code THERMOS⁽¹⁰⁾. Single cell calculations were made for each type of cell, both wet and dry, with and without copper absorber at the cell boundary, in a cylindricized geometry, and with a reflecting boundary condition at the other cell surface.

In general the cross sections calculated by THERMOS are defined as:

$$\bar{\sigma}(r) = \frac{\int_0^{E_{ec}} \sigma(E) \phi(E, r) dE}{\int_0^{E_{ec}} \sqrt{E_0/E} \phi(E, r) dE}$$

where, E_{ec} = upper limit of the thermal neutron spectrum,
taken as 0.683 ev.

E_0 = 0.0253 ev

$\phi(E, r)$ = space-energy distribution of neutrons

FIGURE 11. Radial Flux Plots Derived by Experiment and THERMOS Calculations (Normal Coolant Conditions)

FIGURE 12. Radial Flux Plots Derived by Experiment and THERMOS Calculations (Simulated Process Channel Flooding)

FIGURE 13. Radial Flux Plots Derived by Experiment and THERMOS Calculations (Simulated Process Channel and Gas Vent Flooding)

Region averaged THERMOS cross sections calculated using the previously described technique are presented in Tables IX, X and XI for the basic cell conditions measured in this experiment.

As defined in the previous equation, the values will be 2200 m/sec values unless the cross section is non-1/v for $0 \leq E \leq 0.683$ ev.

1/v Utilization

The 1/v utilization of a cell component is defined as the ratio of the 1/v neutron energy absorption rate in that component, to the sum of the 1/v absorption rates in all cell components. The experimental values of this parameter are derived from the calculated cross section data and the experimentally measured 1/v neutron reaction rate in Copper-63. At space point r the 1/v absorption rate in Copper-63 is given by:

$$\bar{S}A^{63}(r) = C \frac{N_O}{A^{63}} \Lambda_{\sigma}^{63}(r) \int_0^{E_O} \sqrt{E_O/E} \phi(E,r) dE,$$

where C is a space independent normalizing constant.

A similar value of $\bar{S}A^x$ for the material, x, in any given region, may be obtained from the simple ratio:

$$\bar{S}A^x(r) = \frac{\Lambda_{\sigma}^x(r) A^{63}}{\Lambda_{\sigma}^{63}(r) A^x} \bar{S}A^{63}(r)$$

where A is the atomic weight.

The total 1/v absorption rate in material x, $(\text{Abs})^x$, may be obtained for a region by the volume weighted average of $\bar{S}A^x(r)$:

$$(\text{Abs})^x = M^x \frac{\int \bar{S}A^x(r) dV}{\int dV} \quad \text{All of region x}$$

TABLE IX. *Thermos Calculated Cross Sections (Normal Coolant Case)*

Region	Isotope	$\bar{\sigma}_a$	$\bar{\sigma}_a, l/v$	$\hat{\sigma} = \bar{\sigma}_a / \bar{\sigma}_a, l/v$
1	²³⁸ U	1.61830	5.82502 x 10 ⁻¹	2.77818
	²³⁵ U	3.71275 x 10 ⁻²		6.37159 x 10 ⁻²
	Al	1.33976 x 10 ⁻¹		2.30000 x 10 ⁻¹
2	Al	1.41559 x 10 ⁻¹	6.15473 x 10 ⁻¹	2.30001 x 10 ⁻¹
3	H	2.07706 x 10 ⁻¹	6.33247 x 10 ⁻¹	3.27999 x 10 ⁻¹
	O	1.32972 x 10 ⁻⁴		2.09982 x 10 ⁻⁴
4	Al	1.37936 x 10 ⁻¹	5.99721 x 10 ⁻¹	2.30000 x 10 ⁻¹
5	²³⁸ U	1.67701	6.04448 x 10 ⁻¹	2.77446
	²³⁵ U	3.87132 x 10 ⁻²		6.40471 x 10 ⁻²
	Al	1.39023 x 10 ⁻¹		2.30000 x 10 ⁻¹
6	Al	1.49959 x 10 ⁻¹	6.51994 x 10 ⁻¹	2.30001 x 10 ⁻¹
7	H	2.24950 x 10 ⁻¹	6.85824 x 10 ⁻¹	3.28000 x 10 ⁻¹
	O	1.44012 x 10 ⁻⁴		2.09984 x 10 ⁻⁴
8	Zr	1.25169 x 10 ⁻¹	6.95400 x 10 ⁻¹	1.79996 x 10 ⁻¹
	N	1.21698		1.75004
	O	1.46022 x 10 ⁻²		2.09983 x 10 ⁻²
9	C	2.37121 x 10 ⁻³	6.97414 x 10 ⁻¹	3.40000 x 10 ⁻³
	N	1.22050		1.75004
	O	1.46445 x 10 ⁻⁴		2.09983 x 10 ⁻⁴
10	N	1.22117	6.97793 x 10 ⁻¹	1.75005
	O	1.46525 x 10 ⁻⁴		2.09983 x 10 ⁻⁴
11	C	2.37318 x 10 ⁻³	6.97995 x 10 ⁻¹	3.39995 x 10 ⁻³
	N	1.22152		1.75004
	O	1.46567 x 10 ⁻⁴		2.09983 x 10 ⁻⁴
Poison	Cu			3.79

TABLE X. *Thermos Calculated Cross Sections
(Simulated Process Channel Flooding)*

Region	Isotope	$\bar{\sigma}_a$	$\bar{\sigma}_a, \text{l/v}$	$\hat{\sigma} = \bar{\sigma}_a / \bar{\sigma}_a, \text{l/v}$
1	²³⁸ U	1.68689	6.08199×10^{-1}	2.77358
	²³⁵ U	3.86334×10^{-2}		6.35210×10^{-2}
	Al	1.42927×10^{-1}		2.35000×10^{-1}
2	Al	1.50568×10^{-1}	6.40714×10^{-1}	2.35000×10^{-1}
3	H	2.19006×10^{-1}	6.59658×10^{-1}	3.31999×10^{-1}
	O	1.17419×10^{-4}		1.78000×10^{-4}
4	Al	1.47788×10^{-1}	6.28887×10^{-1}	2.34999×10^{-1}
5	²³⁸ U	1.76570	6.37544×10^{-1}	2.76953
	²³⁵ U	4.07396×10^{-2}		6.39008×10^{-2}
	Al	1.49823×10^{-1}		2.35000×10^{-1}
6	Al	1.61308×10^{-1}	6.86419×10^{-1}	2.34999×10^{-1}
7	H	2.39897×10^{-1}	7.22581×10^{-1}	3.32000×10^{-1}
	O	1.28619×10^{-4}		1.77999×10^{-4}
8	Zr	1.40736×10^{-1}	7.48598×10^{-1}	1.87999×10^{-1}
	C	2.54523×10^{-3}		3.40000×10^{-3}
	H	2.48535×10^{-1}		3.32001×10^{-1}
	N	1.38491		1.85000
	O	1.33250×10^{-4}		1.77999×10^{-4}
9	C	2.54646×10^{-3}	7.48960×10^{-1}	3.3999×10^{-3}
	N	1.38558		1.85000
	O	1.33315×10^{-4}		1.78000×10^{-4}
10	N	1.38665	7.49539×10^{-1}	1.85000
	O	1.33418×10^{-4}		1.78000×10^{-4}
11	C	2.54604×10^{-3}	7.48835×10^{-1}	3.40000×10^{-3}
	N	1.38534		1.84999
	O	1.33293×10^{-4}		1.78000×10^{-4}
Poison	Cu			3.79

TABLE XI. Thermos Calculated Cross Sections (Simulated Process Channel and Gas Vent Flooding)

Region	Isotope	$\bar{\sigma}_a$	$\bar{\sigma}_a, \text{l/v}$	$\hat{\sigma} = \bar{\sigma}_a / \bar{\sigma}_a, \text{l/v}$
1	²³⁸ U	1.71612	6.19176×10^{-1}	2.77162
	²³⁵ U	3.94013×10^{-1}		6.36351×10^{-2}
	Al	1.45506×10^{-1}		2.34939×10^{-1}
2	Al	1.53158×10^{-1}	6.51736×10^{-1}	2.35000×10^{-1}
3	H	2.22815×10^{-1}	6.71130×10^{-1}	3.32000×10^{-1}
	O	1.19461×10^{-4}		1.78000×10^{-4}
4	Al	1.50674×10^{-1}	6.41165×10^{-1}	2.35000×10^{-1}
5	²³⁸ U	1.80176	6.51021×10^{-1}	2.76759
	²³⁵ U	4.16940×10^{-2}		6.40440×10^{-2}
	Al	1.52990×10^{-1}		2.35000×10^{-1}
6	Al	1.64597×10^{-1}	7.00414×10^{-1}	2.35000×10^{-1}
7	H	2.44759×10^{-1}	7.37226×10^{-1}	3.32000×10^{-1}
	O	1.31226×10^{-4}		1.78000×10^{-4}
8	Zr	1.43992×10^{-1}	7.65916×10^{-1}	1.88000×10^{-1}
	C	2.60711×10^{-3}		3.39999×10^{-3}
	H	2.54284×10^{-1}		3.32000×10^{-1}
	N	1.41694		1.84999
	O	1.36333×10^{-4}		1.78000×10^{-4}
9	C	2.61672×10^{-3}	7.69624×10^{-1}	3.40000×10^{-3}
	N	1.42381		1.85001
	O	1.36993×10^{-4}		1.78000×10^{-4}
10	C	2.63005×10^{-3}	7.73544×10^{-1}	3.40000×10^{-3}
	H	2.56816×10^{-1}		3.31999×10^{-1}
	O	1.37691×10^{-4}		1.78000×10^{-4}
11	C	2.61976×10^{-3}	7.70516×10^{-1}	3.40001×10^{-3}
	N	1.42546		1.85001
	O	1.37152×10^{-4}		1.78000×10^{-4}
Poison	Cu			3.79

Finally, the the $1/v$ utilization of material x is

$$f^x = (\text{Abs})^x / \sum_i (\text{Abs})_i$$

Absorption rates for all cell components and $1/v$ utilizations of these components are presented in Tables XII, XIII and XIV.

Determination of k_∞

In a simple uranium fueled system, the equations for calculating k_∞ can be derived from the four factor formula⁽¹¹⁾:

$$k_\infty = \eta \epsilon p f$$

It is assumed that the addition of copper to the boundary of the supercell will change only the thermal utilization. Since the multiplication factor, (k_∞') of the supercell with the correct mass of copper (M_o) is unity;

$$k_\infty' = \eta \epsilon p f' = 1$$

Therefore, k_∞ has been derived^(1,2) as the ratio of the unpoisoned to poison thermal utilizations of the supercell,

$$k_\infty = \frac{f}{f'}, \text{ where}$$

f = the $1/v$ utilization of the unpoisoned supercell;

f' = the $1/v$ utilization of the poisoned supercell.

The derivation of the $f_{1/v}$ in the equation above is based on the assumption that the absorption rates in all the cell components, except for the resonance absorption in ^{238}U , can be calculated using the flux measured by a detector whose absorption cross section varies as $1/\sqrt{E}$ multiplied by the effective 2200 m/sec cross section calculated by THERMOS. The material used as the absorber in the determination of k_∞ $1/v$ must also have an effective cross section that varies as $1/\sqrt{E}$. The use of the four factor formula in the derivation of k_∞ $1/v$ implies that:

$$k_\infty 1/v = \eta_{1/v} \epsilon P_{\text{non } 1/v} f_{1/v}$$

TABLE XII. Experimental $1/\nu$ Absorption Rates and Thermal Utilization
(Normal Coolant Case)

Region	Isotope	$\hat{\sigma}_x(r)$	A_x	$\overline{SA}_{63}^{1/\nu}(r)$	$\overline{SA}_x(r)$	m_x	Relative Absorption	$Ab_x/\Sigma_x Ab_x$
1	^{238}U	2.77818	238.0132	1.3977	2.2763×10^{-1}	3023.7549	6.8829×10^2	4.3451×10^{-2}
	^{235}U	6.37159 $\times 10^2$	235.0439		5.2865×10^1	24.3851	1.2891×10^3	8.1379×10^{-2}
	Al	2.30000 $\times 10^{-1}$	26.9815		1.6624×10^{-1}	20.8880	3.4724	2.1921×10^{-4}
2	Al	2.30001 $\times 10^{-1}$	26.9815	1.685	2.0041×10^{-1}	73.474	1.4725×10^1	9.2956×10^{-4}
3	H	3.27999 $\times 10^{-1}$	1.008	1.8373	8.3415	15.506	1.2934×10^2	8.1650×10^{-3}
	O	2.09982 $\times 10^{-4}$	16.000		3.3643×10^{-4}	123.063	4.1402×10^{-2}	2.6136×10^{-6}
4	Al	2.30000 $\times 10^{-1}$	26.9815	1.648	1.9647×10^{-1}	141.870	2.7873×10^1	1.7596×10^{-3}
5	^{238}U	2.77446	238.0132	1.7660	2.8722×10^{-1}	15460.766	4.4407×10^3	2.8033×10^{-1}
	^{235}U	6.40471 $\times 10^2$	235.0439		6.7142×10^1	124.6836	8.3715×10^3	5.2848×10^{-1}
	Al	2.30000 $\times 10^{-1}$	26.9815		2.1004×10^{-1}	122.720	2.5776×10^1	1.6272×10^{-3}
6	Al	2.30001 $\times 10^{-1}$	26.9815	2.369	2.8176×10^{-1}	266.880	7.5196×10^1	4.7470×10^{-3}
7	H	3.28000 $\times 10^{-1}$	1.008	2.7400	1.2440×10^{-1}	26.070	3.2431×10^2	2.0473×10^{-2}
	O	2.09984 $\times 10^{-4}$	16.000		5.0173×10^{-4}	206.907	1.0381×10^{-1}	6.5534×10^{-6}
8	Zr	1.79996 $\times 10^{-1}$	91.220	3.032	8.3475×10^{-2}	771.014	6.4360×10^1	4.0629×10^{-3}
	N	1.75004	14.008	3.1775	5.5387	0.33719	1.8676	1.1790×10^{-4}
	O	2.09983 $\times 10^{-2}$	16.000		5.8184×10^{-2}	0.05348	3.1117×10^{-3}	1.9644×10^{-7}
9	C	3.40000 $\times 10^{-3}$	12.011	3.4397	1.3585×10^{-2}	3242.25	4.4047×10^1	2.7806×10^{-3}
	N	1.75004	14.008		5.9958	0.4674	2.8024	1.7691×10^{-4}
	O	2.09983 $\times 10^{-4}$	16.000		6.2985×10^{-4}	0.0741	4.6672×10^{-5}	2.9463×10^{-9}
10	N	1.75005	14.008	3.5723	6.2269	0.2740	1.7062	1.0771×10^{-4}
	O	2.09983 $\times 10^{-4}$	16.000		6.5413×10^{-4}	0.0435	2.8455×10^{-5}	1.7963×10^{-9}
11	C	3.39995 $\times 10^{-3}$	12.011	4.0035	1.5812×10^{-2}	19836.900	3.1366×10^2	1.9801×10^{-2}
	N	1.75004	14.008		6.9785	3.131	2.1850×10^1	1.3794×10^{-3}
	O	2.09983 $\times 10^{-4}$	16.000		7.3309×10^{-4}	0.497	3.6435×10^{-4}	2.3001×10^{-8}
Totals						15840.7478		.9999
Poison	Cu	3.79	63.540	4.124	3.4321	-54.781	-1.8801×10^2	

f = .9336
f' = .9449
k_∞ = .9881 (without corrections for end effects)

TABLE XVIII. Experimental $1/\nu$ Absorption Rates and Thermal Utilization
(Simulated Process Channel Floodings)

Region	Isotope	$\sigma_x(r)$	A_x	$\overline{SA}_{63}^{1/\nu}(r)$	$\overline{SA}_x(r)$	m_x	Relative Absorption	Ab_x/ϵ_{xAbx}
1	^{238}U	2.77358	238.0132	1.6700	2.7152×10^{-1}	3023.7549	8.2102×10^2	4.0402×10^{-2}
	^{235}U	6.35210×10^2	235.0439		6.2971×10^{-1}	24.3851	1.5355×10^3	7.5561×10^{-2}
	Al	2.35000×10^{-1}	26.9815		2.0294×10^{-1}	20.8880	4.2390	2.0860×10^{-4}
2	Al	2.35000×10^{-1}	26.9815	1.9719	2.3963×10^{-1}	73.474	1.7607×10^1	8.6643×10^{-4}
3	H	3.31999×10^{-1}	1.008	2.1676	9.9611	15.506	1.5446×10^2	7.6008×10^{-2}
	O	1.78000×10^{-4}	16.000		3.3646×10^{-4}	123.063	4.1406×10^{-2}	2.0376×10^{-6}
4	Al	2.34999×10^{-1}	26.9815	1.9729	2.3975×10^{-1}	141.870	3.4013×10^1	1.6738×10^{-3}
5	^{238}U	2.76953	238.0132	2.1683	3.5203×10^{-1}	15460.766	5.4426×10^3	2.6783×10^{-1}
	^{235}U	6.39008×10^2	235.0439		8.2249×10^{-1}	124.6836	1.0255×10^4	5.0464×10^{-1}
	Al	2.35000×10^{-1}	26.9815		2.6350×10^{-1}	122.720	3.2336×10^1	1.5912×10^{-3}
6	Al	2.34999×10^{-1}	26.9815	2.9029	3.5276×10^{-1}	266.880	9.4146×10^1	4.6328×10^{-3}
7	H	3.32000×10^{-1}	1.008	3.4122	1.5681×10^{-1}	26.070	4.0880×10^2	2.0117×10^{-2}
	O	1.77999×10^{-4}	16.000		5.2965×10^{-4}	206.907	1.0959×10^{-1}	5.3928×10^{-6}
8	Zr	1.87999×10^{-1}	91.220	4.2976	1.2358×10^{-1}	771.014	9.5281×10^1	4.6887×10^{-3}
	C	3.40000×10^{-3}	12.011	5.1201	2.0222×10^{-2}	213.9724	4.3270	2.1293×10^{-4}
	H	3.32001×10^{-1}	1.008		2.3529×10^1	35.9136	8.4502×10^2	4.1583×10^{-2}
	N	1.85000	14.008		9.4347	0.0695	6.5571×10^{-1}	3.2267×10^{-5}
	O	1.77999×10^{-4}	16.000		7.9475×10^{-4}	0.0110	8.7422×10^{-6}	4.3020×10^{-10}
				5.4246	2.1425×10^{-2}	3242.250	6.9465×10^1	3.4183×10^{-3}
9	C	3.39999×10^{-3}	12.011		9.9958	0.4674	4.6720	2.2991×10^{-4}
	N	1.85000	14.008		8.4202 $\times 10^{-4}$	0.0741	6.2393×10^{-5}	3.0703×10^{-9}
	O	1.78000×10^{-4}	16.000					
10	N	1.85000	14.008	5.5237	1.0178×10^{-1}	0.2740	2.7889	1.3724×10^{-4}
	O	1.78000×10^{-4}	16.000		8.5740×10^{-4}	0.0435	3.7297×10^{-5}	1.8354×10^{-9}
11	C	3.40000×10^{-3}	12.011	5.9346	2.3439×10^{-2}	19836.900	4.6496×10^2	2.2880×10^{-2}
	N	1.84999	14.008		1.0935×10^{-1}	3.131	3.4239×10^1	1.6849×10^{-3}
	O	1.78000×10^{-4}	16.000		9.2118×10^{-4}	0.497	4.5783×10^{-4}	2.2529×10^{-8}
Totals							20321.4268	.9999
Poison	Cu	3.79	63.540	6.1009	5.0774	+ 65.676	333.4633	

$$f = .8884$$

$$f' = .8741$$

$$k_{\infty} = 1.0164(\text{without corrections for end effects})$$

TABLE XIV.
Experimental $1/\nu$ Absorption Rates and Thermal Utilization
(Simulated Process Channel and Gas Vent Floodings)

Region	Isotope	$\hat{\sigma}_x(r)$	A_x	$\overline{SA}_{63}^{1/\nu}(r)$	$\overline{SA}_x(r)$	m_x	Relative Absorption	$Ab_x/\overline{r}_{Ab_x}$
1	²³⁸ U	2.77162	238.0132	1.7157	2.7877 x 10 ⁻¹	3023.7549	8.4294 x 10 ²	3.5419 x 10 ⁻²
	²³⁵ U	6.36351 x 10 ²	235.0439	6.4814 x 10 ¹	6.4814 x 10 ¹	24.3851	1.5805 x 10 ³	6.6409 x 10 ⁻²
	Al	2.34999 x 10 ⁻¹	26.9815	2.0851 x 10 ⁻¹	2.0851 x 10 ⁻¹	20.8880	4.3553	1.8300 x 10 ⁻⁴
2	Al	2.35000 x 10 ⁻¹	26.9815	2.212	2.6882 x 10 ⁻¹	73.474	1.9751 x 10 ¹	8.2991 x 10 ⁻⁴
3	H	3.32000 x 10 ⁻¹	1.005	2.4303	1.1169 x 10 ⁻¹	15.506	1.7319 x 10 ²	7.2769 x 10 ⁻³
	O	1.78000 x 10 ⁻⁴	16.000	3.7726 x 10 ⁻⁴	3.7726 x 10 ⁻⁴	123.663	4.6653 x 10 ⁻²	1.9602 x 10 ⁻⁶
4	Al	2.35000 x 10 ⁻¹	26.9815	2.182	2.6518 x 10 ⁻¹	141.870	3.7621 x 10 ¹	1.5807 x 10 ⁻³
5	²³⁸ U	2.76759	238.0132	2.4657	4.0005 x 10 ⁻¹	15460.766	6.1652 x 10 ³	2.5989 x 10 ⁻¹
	²³⁵ U	6.40440 x 10 ²	235.0439	9.3745 x 10 ¹	9.3745 x 10 ¹	124.6836	1.1688 x 10 ⁴	4.9112 x 10 ⁻¹
	Al	2.35000 x 10 ⁻¹	26.9815	2.9965 x 10 ⁻¹	2.9965 x 10 ⁻¹	122.720	3.6774 x 10 ¹	1.5451 x 10 ⁻³
6	Al	2.35000 x 10 ⁻¹	26.9815	3.438	4.1782 x 10 ⁻¹	266.880	1.1151 x 10 ²	4.6853 x 10 ⁻³
7	H	3.32000 x 10 ⁻¹	1.008	4.4799	2.0588 x 10 ¹	26.070	5.3674 x 10 ²	2.2553 x 10 ⁻²
	O	1.78000 x 10 ⁻⁴	16.000	6.9542 x 10 ⁻⁴	6.9542 x 10 ⁻⁴	206.907	1.4389 x 10 ⁻¹	6.0458 x 10 ⁻⁶
8	Zr	1.88000 x 10 ⁻¹	91.220	5.4444	1.5657 x 10 ⁻¹	771.014	1.2071 x 10 ²	5.0721 x 10 ⁻³
	C	3.39999 x 10 ⁻³	12.011	6.0235	2.3792 x 10 ⁻²	213.9724	5.0908	2.1390 x 10 ⁻⁴
	H	3.32000 x 10 ⁻¹	1.008	2.7682 x 10 ¹	2.7682 x 10 ¹	35.9136	9.9418 x 10 ²	4.1773 x 10 ⁻²
	N	1.84999	14.008	1.1100 x 10 ¹	1.1100 x 10 ¹	0.0695	7.7145 x 10 ⁻¹	3.2415 x 10 ⁻⁵
	O	1.78000 x 10 ⁻⁴	16.000	9.3503 x 10 ⁻⁴	9.3503 x 10 ⁻⁴	0.0110	1.0285 x 10 ⁻⁵	4.3217 x 10 ⁻¹⁰
9	C	3.40000 x 10 ⁻³	12.011	6.4867	2.5621 x 10 ⁻²	3242.250	8.3071 x 10 ¹	3.4904 x 10 ⁻³
	N	1.85001	14.008	1.1954 x 10 ¹	1.1954 x 10 ¹	0.4669	5.5811	2.3451 x 10 ⁻⁴
	O	1.78000 x 10 ⁻⁴	16.000	1.0069 x 10 ⁻³	1.0069 x 10 ⁻³	0.0741	7.4614 x 10 ⁻⁵	3.1351 x 10 ⁻⁹
10	C	3.40000 x 10 ⁻³	12.011	6.9045	2.7272 x 10 ⁻²	177.052	4.8285	2.0288 x 10 ⁻⁴
	H	3.31999 x 10 ⁻¹	1.008	3.1731 x 10 ¹	3.1731 x 10 ¹	23.772	7.5432 x 10 ²	3.1695 x 10 ⁻²
	O	1.78000 x 10 ⁻⁴	16.000	1.0718 x 10 ⁻³	1.0718 x 10 ⁻³	94.340	1.0111 x 10 ⁻¹	4.2485 x 10 ⁻⁶
11	C	3.40001 x 10 ⁻³	12.011	7.2976	2.8824 x 10 ⁻²	19836.900	5.7178 x 10 ¹	2.4025 x 10 ⁻²
	N	1.85001	14.008	1.3448 x 10 ¹	1.3448 x 10 ¹	3.1147	5.1886 x 10 ⁻⁴	1.7600 x 10 ⁻³
	O	1.78000 x 10 ⁻⁴	16.000	1.1328 x 10 ⁻³	1.1328 x 10 ⁻³	0.4940	5.5961 x 10 ⁻⁴	2.3514 x 10 ⁻⁸
Poison			3.79	7.3692	6.1333	Totals	23799.4982	1.0000
	Cu		63.540	7.3692	6.1333	47.5704	291.7635	

$$f = .8518$$

$$f' = .8417$$

$$k_{\infty} = 1.0121 \text{ (without corrections for end effects)}$$

Therefore all non- $1/v$ epithermal absorption is accounted for in the resonance escape probability $p_{\text{non}1/v}$.

The equation relating the thermal utilizations in the poisoned and unpoisoned cells with k_{∞} can be rewritten in terms of absorption rates:

$$k_{\infty} - 1 = \frac{(Abs)'}{\sum (Abs)_i} + \frac{\sum_i [(Abs)_{i'} - (Abs)_i]}{\sum (Abs)_i}$$

$(Abs)'$ = relative $1/v$ absorption rate in copper poison.

$(Abs)_{i'}$ = relative $1/v$ absorption rate in i th component of the test cell with copper neutron absorber.

$(Abs)_i$ = relative $1/v$ absorption rate in the i th component of the test cell without copper neutron absorber.

A condition in this equation is that the absorption rates in the fuel for the poison and unpoisoned case are normalized to be equal.

Values for k_{∞} determined from this PCTR experiment are presented in Table I of the summary.

k_{∞} DETERMINED FROM ADJOINT WEIGHTED CROSS SECTION TECHNIQUE

Adjoint Weighted Cross Section Parameters

Information about neutron multiplication properties of a medium can also be obtained without having to add an absorber to the medium by measuring the adjoint weighted excess neutron production cross section, defined here as $\langle \Sigma_p \rangle^{(2,9)}$. The infinite medium excess neutron multiplication factor, $k_{\infty} - 1$, can then be obtained from the experimentally determined $\langle \Sigma_p \rangle$ by making an appropriate leakage dependent correction:

$$k_{\infty} - 1 = \frac{\langle \Sigma_p \rangle_o A_{2a}^s V^{\text{cell}}}{A_2^{\text{cell}} V_a \Sigma_{oa}} + g(\Delta\phi, \Delta\phi^+) + \frac{\tau_B^2}{1 + \tau_B^2}$$

where the first term on the right hand side of the equation is the excess production per unit thermal absorption in the cell. The second term is a correction for any mismatch between the flux and/or the adjoint in the test cavity and the equilibrium flux and/or adjoint characteristic of the medium. Foil measurements indicated that flux mismatch was negligible in this experiment. The third term is a calculated correction for leakage.

The expression for $\langle \Sigma_p \rangle$ in terms of measured and calculated quantities, are

$$\langle \Sigma_p \rangle = \frac{\Delta \rho_{\text{cell}}}{\Delta \rho_a} \frac{V_a \Sigma_{\text{oa}}}{V_{\text{cell}}} \frac{A_{2a} + \rho A_{1a}}{A_{2a}^s}$$

This cross section is normalized to the 2200 m/sec cross section of the absorber, Σ_{oa} ; the same normalization of calculated values is necessary for comparison to measured values. The quantities are defined as follows:

- $\Delta \rho_{\text{cell}}$ = Reactivity worth of center test cell after nitrogen corrections.
- $\Delta \rho_a$ = Reactivity worth of absorber in center cell cavity.
- V_a = Volume of absorber (copper).
- Σ_{oa} = Microscopic 2200 m/sec absorption cross section of absorber.
- V_{cell} = Volume of center test cell.
- A_{2a}^s = Thermal absorption rate of absorber at cell surface.
- $A_{\text{cell}}^{\text{cell}}$ = Thermal absorption rate of cell components.
- A_1^a = Epithermal absorption rate in absorber.
- p = Resonance escape probability for test lattices (MOFDA calculation)⁽¹³⁾
- T = Age of neutrons in medium (MOFDA calculation).
- B^2 = Material buckling of lattice and fuel (MOFDA calculation)

The adjoint weighted cross section technique was used to measure the infinite medium neutron multiplication factor of four different cell conditions.

Normal coolant case

Simulated flooding around process tube

Simulated flooding around process tube and in gas vents

Dry cell case

Data and Resulting k_{∞}

The measured parameters for the above conditions are listed in Table XV with the respective k_{∞} calculations. For calculational ease a new quantity is defined for k_{∞} ; that is,

$$k_{\infty} = \frac{\langle \Sigma_p \rangle}{(\Sigma_a)_o^{\text{cell}}} + g (\Delta\phi, \Delta\phi^+) + \frac{T_B^2}{1+TB^2}$$

$$\text{where } (\Sigma_a)_o^{\text{cell}} = \frac{A_2^{\text{cell}} v_a^s \Sigma_{oa}}{A_{2a}^s V_{\text{cell}}}$$

if $(\Sigma_a)_o^{\text{cell}}$ is calculated by THERMOS as is done in the dry cell experiment when component absorption rates were not measured,

$$(\Sigma_a)_o^{\text{cell}} = \left[\bar{\Sigma}_o^{\text{cell}} \frac{\sigma_o^{1/v}}{\sigma_{1/v}^{\text{cell surface}}} \times \frac{\phi_{\text{cell}}}{\phi_{\text{cell surface}}} \right]$$

COMPARISON OF ACTUAL WATER FLOODING WITH SIMULATED FLOODING

Description

After all cell measurements had been completed in the PCTR, the center fuel channel and graphite bars were removed with the adjacent, surrounding graphite. This latter material was cut to permit the immersion of the center test cell and for the whole

TABLE XV. Measured Parameters for Adjoint Weighted Neutron Production Cross Section Method to Determine k_{∞}

Parameter	15 Cell Condition			
	Normal Coolant	Process Channel Flooding	Process Channel and Gas Vent	Dry Cells
$\Delta\rho_{\text{cell}} (\%)$	- 1.011 ± 0.076	+ 1.610 ± 0.076	1.099 ± 0.081	- 5.595 ± 0.075
$\Delta\rho_{\text{in cavity}}^{\text{Cu}} (\%)$	- 2.454 + 0.057	- 3.230 + 0.057	- 3.658 ± 0.057	- 1.939 ± 0.057
$V_{\text{aOa}}^{\text{cavity}} (\text{cm})^2$	4.676 ± 0.148	4.676 ± 0.148	4.676 ± 0.148	4.676 ± 0.148
$V_{\text{Oa}}^{\text{surface}}$	9.326	9.326	9.326	8.326
$V_{\text{cell}} (\text{cm})^3$	16,352.2	16,352.2	16,352.2	16,352.2
A_2^{a}	3.594	5.527	6.921	2.537
A_1^{a}	0.459	0.440	0.452	0.472
ρ (MOFDA)	0.7753	0.8108	0.8351	0.7039
$\Lambda_{2\text{a}}^{\text{s}}$	843.6	1239.2	1524.15	672.007
A_2^{cell}	14,166.7 ± 123.5	18,655.3 ± 155.9	22,218.8 ± 179.5	11,571.34 (THERMOS calc)
T (MOFDA)	236.6	196.3	169.2	359.5
B^2	70.4×10^{-6}	144.7×10^{-6}	161.5×10^{-6}	$- 96.4 \times 10^{-6}$
$\langle \Sigma_p \rangle$	.000118	.000146	.0000887	.000760
Σ_{a}	.00871	.00746	.00710	.00982
$\frac{\langle \Sigma_p \rangle}{\Sigma_{\text{a}}}$	- .0135 ± .0012	+ .0196 ± .0012	+ .0125 ± .0010	- .0774 ± .0036
k_{∞}	0.987	1.017	1.012	0.923
End Effect Correction	- .0003	- .010	- .012	- .012
Corrected k_{∞}	0.984	1.007	1.000	0.911

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assembly (i.e., tank and center cell) to be inserted in the reactor. The center cell plus the tank with the separable element and foil holders are shown in Figure 14. The photograph is different than actually was the case since it shows the lucite and polyethylene wrap in place around the process tube and in the gas vents, respectively. The flooding simulators were not used in these measurements; the can was filled with water after inserting the graphite and fuel so that all the vents and area around the process tube would contain water. The reactivity measurements and foil irradiations were accomplished with water in the test cell.

Results

The statistics and measured results of the water flooded lattice are listed in Table XVI without too much explanation. The parameters have been defined in the sections above concerned with the normal coolant and simulated flooding conditions. It should be noted that only the center test cell could be flooded and simulated flooding conditions with polyethylene and lucite were used in all buffer cells and regions.

TABLE XVI. *Statistics and Results of Actual Water Flooding in PCTR Test Lattice*

Thermal Utilization	0.807 ± 0.011
k_{∞} (null reactivity measurement)	0.967 ± 0.003
k_{∞} (non-poison measurement)	0.967 ± 0.003
$M_{(o)}$ without tank and simulated flooding conditions	+ 46 ± 4 gram copper
$M_{(o)}$ with tank in place and simulated flooding conditions	+ 47 ± 4 gram copper
$M_{(o)}$ with tank in place and water flooding conditions (buffer cells simulated flooding with polyethylene and lucite)	- 97 ± 2 gram copper
$(M_{(o)})^{1/v}$ with tank in place and actual water flooding conditions (buffer cells simulated flooding with polyethylene and lucite)	- 98 ± 2 gram copper
Volume of water put into tank with center test cell in place	870 cc

FIGURE 14. Center Cell and Aluminum Tank Used for the Experimental Measurement of Actual Water Flooding Effects

The measurements with actual water flooding was a one-shot attempt because the graphite immediately began to absorb the water and conditions in the center test cell did not remain constant.

After the reactivity measurements the experiment proceeded with the foil irradiations necessary to derive the neutron utilization of the cell components. Following the irradiations there was an attempt to return to original cell conditions before the water was added. At that time the graphite components of the center cell were weighed and then put into an oven to dry out. Following the drying period the components were reweighed with the following results:

<u>Component</u>	<u>Condition</u>	<u>Weight (grams)</u>
Hole Bar	Before Flooding	3,242.40
Hole Bar	Before Drying	3,242.40
Hole Bar	After Drying	3,242.25
Outer Bar	Before Flooding	19,850.90
Outer Bar	Before Drying	20,232.85
Outer Bar	After Drying	19,836.90
Volume of Water Absorbed in Outer Bar		395.95 cc.

Comparison of Sub-Cadmium Measured Activities With THERMOS Calculations for Water Flooded Conditions

There was no certainty of the absorption rate of water into the graphite so that the actual cell conditions which existed at the time of the foil irradiations were not exactly known. Therefore the foil data was compared with the thermal flux traverses derived by two different THERMOS computer code calculations, one without water in the outer graphite and the other with 395 cc of water distributed in the outer graphite. The plots of these comparisons are graphed in Figures 15 and 16. These results indicate the water was probably in the outer graphite during the foil irradiations. Therefore the cross sections derived for the calculation of neutron utilization

FIGURE 15. Radial Flux Plots Derived by Experiment and THERMOS Calculations (Actual Water Flooded Lattice and 395 cc Water In Outer Graphite)

FIGURE 16. Relative Flux Plots Derived by Experiment and THERMOS Calculations (Actual Water Flooded Lattice Without Water Absorbed in Graphite)

were taken from the THERMOS case with water in the outer graphite.

Cross Sections and Utilizations

The cross sections (Table XVII) necessary to derive the neutron utilization of the cell components were taken from the THERMOS calculation based on the condition that the outer graphite in the flooded lattice had absorbed 395 cc of water. The neutron utilization (Table XVIII) were calculated, based on the same assumption.

TABLE XVII. *Thermos Calculated Cross Sections*

<u>Region</u>	<u>Isotope</u>	$\bar{\sigma}_a$	$\bar{\sigma}_{al/v}$	$\hat{\sigma} = \bar{\sigma}_a / \bar{\sigma}_{al/v}$
1	U ²³⁸	1.75762	6.34807×10^{-1}	2.76875
	U ²³⁵	4.08359×10^2		6.43280×10^2
	Al	1.46006×10^{-1}		2.30001×10^{-1}
2	Al	1.53598×10^{-1}	6.67817×10^{-1}	2.30000×10^{-1}
3	H	2.25617×10^{-1}	6.87856×10^{-1}	3.28000×10^{-1}
	O	1.44438×10^{-4}		2.09983×10^{-4}
4	Al	1.51599×10^{-1}	6.59127×10^{-1}	2.30000×10^{-1}
5	U ²³⁸	1.85559	6.71187×10^{-1}	2.76464
	U ²³⁵	4.35215×10^2		6.48426×10^2
	Al	1.54373×10^{-1}		2.30000×10^{-1}
6	Al	1.66113×10^{-1}	7.22228×10^{-1}	2.30001×10^{-1}
7	H	2.49279×10^{-1}	7.59996×10^{-1}	3.28000×10^{-1}
	O	1.59587×10^{-4}		2.09984×10^{-4}
8	Zr	1.43125×10^{-1}	7.95155×10^{-1}	1.79996×10^{-1}
	H	2.60811×10^{-1}		3.28000×10^{-1}
	O	1.66969×10^{-4}		2.09983×10^{-4}
9	C	2.72111×10^{-3}	8.00325×10^{-1}	3.40001×10^{-3}
	N	1.40060		1.75004
	O	1.68055×10^{-4}		2.09983×10^{-4}
10	H	2.64330×10^{-1}	8.05886×10^{-1}	3.27999×10^{-1}
	O	1.69223×10^{-4}		2.09984×10^{-4}
11	C	2.73196×10^{-3}	8.03518×10^{-1}	3.40000×10^{-3}
	H	2.63554×10^{-1}		3.28000×10^{-1}
	O	1.68725×10^{-4}		2.09983×10^{-4}
	N	1.40619		1.75004
Poison	Cu			3.79

TABLE XVIII. Experimental $1/\nu$ Absorption Rates and Utilizations
(Water Flooding Conditions)

Region	Isotope	$\hat{\sigma}_x(r)$	A_x	$\overline{SA}_{63}^{1/\nu}(r)$	$\overline{SA}_x(r)$	m_x	Relative Absorption	$Ab_x/\tau_x^{Ab}x$
1	²³⁸ U	2.76875	238.0132	1.6544	2.6854×10^{-1}	3023.7549	8.1199×10^2	3.3899×10^{-2}
	²³⁵ U	6.43280 $\times 10^2$	235.0439		6.3179×10^1	24.3851	1.5406×10^3	6.4318×10^{-2}
	Al	2.30001 $\times 10^{-1}$	26.9815		1.9678×10^{-1}	20.888	4.1103	1.7160×10^{-4}
2	Al	2.30000 $\times 10^{-1}$	26.9815	2.0008	2.3798×10^{-1}	73.474	1.7485×10^1	7.2999×10^{-4}
3	H	3.28000 $\times 10^{-1}$	1.008	2.2749	1.0329×10^1	15.506	1.6016×10^2	6.6864×10^{-3}
	O	2.09983 $\times 10^{-4}$	16.000		4.1659×10^{-4}	123.063	5.1266×10^{-2}	2.1403×10^{-6}
4	Al	2.30000 $\times 10^{-1}$	26.9815	2.0556	2.4450×10^{-1}	141.87	3.4687×10^1	1.4481×10^{-3}
5	²³⁸ U	2.76464	238.0132	2.3223	3.7639×10^{-1}	15460.766	5.8192×10^3	2.4294×10^{-1}
	²³⁵ U	6.48426 $\times 10^2$	235.0439		8.9394×10^1	124.6836	1.1146×10^4	4.6533×10^{-1}
	Al	2.30000 $\times 10^{-1}$	26.9815		2.7622×10^{-1}	122.720	3.3898×10^1	1.4152×10^{-3}
6	Al	2.30001 $\times 10^{-1}$	26.9815	3.193	3.7979×10^{-1}	266.880	1.0136×10^2	4.2315×10^{-3}
7	H	3.28000 $\times 10^{-1}$	1.008	4.054	1.8407×10^1	26.070	4.7986×10^2	2.0034×10^{-2}
	O	2.09983 $\times 10^{-4}$	16.000		7.4238×10^{-4}	206.907	1.5360×10^{-1}	6.4127×10^{-6}
8	²³⁸ U	1.79996 $\times 10^{-1}$	91.220	5.0896	1.4013×10^{-1}	771.014	1.0804×10^2	4.5106×10^{-3}
	H	3.28000 $\times 10^{-1}$	1.008	5.4812	2.4887×10^1	37.989	9.4542×10^2	3.9470×10^{-2}
	O	2.09983 $\times 10^{-4}$	16.000		1.0037×10^{-3}	301.503	3.0263×10^{-1}	1.2634×10^{-5}
9	C	3.40001 $\times 10^{-3}$	12.011	6.6535	2.6280×10^{-2}	3055.717	8.0305×10^1	3.3526×10^{-3}
	N	1.75004	14.008		1.1598×10^{-3}	0.434	5.0337×10^{-4}	2.1015×10^{-9}
	O	2.09983 $\times 10^{-4}$	16.000		1.2184×10^{-3}	0.109	1.3281×10^{-4}	5.5445×10^{-9}
10	H	3.27999 $\times 10^{-1}$	1.008	7.2169	3.2767×10^1	30.875	1.0117×10^3	4.2237×10^{-2}
	O	2.09984 $\times 10^{-4}$	16.000		1.3216×10^{-3}	245.037	3.2384×10^{-1}	1.3520×10^{-5}
11	C	3.40000 $\times 10^{-3}$	12.011	7.7292	3.0529×10^{-2}	19836.900	6.0560×10^2	2.5283×10^{-2}
	H	3.28000 $\times 10^{-1}$	1.008		3.5093×10^1	28.719	1.0078×10^3	4.2076×10^{-2}
	O	2.09983 $\times 10^{-4}$	16.000		1.4154×10^{-3}	228.384	3.2325×10^{-1}	1.3495×10^{-5}
	N	1.75004	14.008		1.3474×10^1	2.859	3.8521×10^1	1.6082×10^{-3}
Poison	Cu	3.79	63.540	7.8593	6.5412	Totals	23952.9694	1.00000001
						- 98.724	- 645.7734	

$$f_+ = 0.8065$$

$$f_- = 0.8288$$

$$k_\infty = 0.973 \quad (\text{without corrections for end effects})$$

APPENDIX A

Corrections and System ErrorsA. Nitrogen Corrections

Nitrogen affects the null reactivity values of the cells in two ways; air occupies the void spaces in the graphite and is a neutron absorber, and when the center cell is removed, ambient air enters and fills the cavity. The measured values of k_{∞} for the supercell in the PCTR are for such a lattice stacked in an air environment. To obtain the values of k_{∞} for these lattices stacked in a vacuum environment (or helium), the effect of the l/v utilization of nitrogen in the cell (Tables XII, XIII, XIV and XVII) should be removed. The change is approximately 2.0 mk in normal coolant conditions.

The determination of the reactivity worth of the nitrogen, which fills the cavity formed by removal of the central supercell, $\Delta\rho_N$, is inferred from a copper sensitivity, S_{Cu}^{cavity} , measured value using the expression:

$$\Delta\rho_N = D C \frac{p}{T} (M_N) (1-C) S_{Cu}^{cavity}$$

where D = thermal disadvantage factor for the thickness of copper used in the determination of $S_{Cu}^{cavity} = 1.0110$.

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

$\Delta\rho_{Cu}^{cavity}$ = reactivity worth (¢) of mass of copper, M_{Cu}^{cavity} , in the supercell cavity

p = atmospheric pressure during reactivity measurement, mb;

T = ambient temperature in the cavity, °K

M_n = mass of nitrogen (at standard temperature and pressure) = 16.72 g

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

σ_o^N = 2200 m/sec microscopic absorption cross section of nitrogen = 1.88 barns

σ_o^{Cu} = 2200 m/sec microscopic absorption cross section of natural copper = 3.79 barns

A^{Cu}, A^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 epi-thermal energy dependance of the absorption cross section of natural copper, approximated by:

$$1-C = 1 - \frac{m_1}{m_2} \frac{RI_{ex}^{Cu}}{RI_{epi-Cd}^{Cu} (Cdr-1)},$$

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 = 0.7753 as calculated with MOFDA⁽¹³⁾.

RI_{ex}^{Cu} = effective excess resonance integral of natural copper for the thickness of copper used in measuring $S_{Cu}^{cavity} = 1.3705$ b.

RI_{epi-Cd}^{Cu} = effective epi-cadmium resonance integral of natural copper for the thickness of copper used in measuring $S_{Cu}^{cavity} = 2.8805$ b.

Cdr = cadmium ratio of copper in the cavity, for the thickness of copper used in measuring S_{Cu}^{cavity} .

CdR =   9.188 for normal coolant conditions
              13.535 for simulated flooding conditions
                                 around process tube
              16.255 for simulated flooding conditions
                                 around process tube and gas vent
              6.379 for dry cell conditions

B. 1/v Mass Equivalent of Copper

The requirement that the material used as absorber in the determination of $k_{\infty 1/v}$ have an effective cross section that varies as $1/\sqrt{E}$, makes it necessary to define a 1/v equivalent mass of copper, $M_{1/v}$, so that its reactivity coefficient is equivalent to the correct mass of copper, M_O .

$$M_{1/v} SA_{1/v} M_2 = M_O (SA_{1/v} M_2 + SA_{res} M_1)$$

Account is taken of the worth of epi-thermal resonance absorptions in copper relative to the worth of 1/v absorptions. As shown in the previous notation,

$$M_{1/v} = M_O \left[1 + \left(\frac{m_1}{m_2} \right) \left(\frac{RI_{ex}^{Cu}}{CdR \cdot RI_{epi-Cd}^{Cu} - RI_{ex}} \right) \right]$$

For this experiment 0.010 inch thick copper strips were placed at the boundary of the cell and foils were placed in these strips. The effective resonance integrals were taken from measurements by Bennett⁽¹⁶⁾. Values for $M_{1/v}$ are only a few percent greater than M_O and are listed in Table II.

C. Counter Efficiency for Dissected Foils

The irradiated copper foils used to measure the relative reaction rates in the fuel had a specific

activity which was a function of radial symmetry, primarily due to disadvantage factors in the fuel. The distribution of the activity in a detector foil affects the over-all efficiency of the scintillation counting system, because the counter system varies with distance from the center of the crystal. Copper foils irradiated in the external thermal column of the PCTR have a constant specific activity with respect to the radial symmetry. Therefore a counter efficiency factor must be removed from the measured data in order to obtain relative reaction rates in the fuel.

The method of correction was developed by Newman⁽¹⁴⁾ using data measured by Bennett as follows:

The observed specific activity for a given geometry shaped detector foil at a given height above the crystal can be expressed as the specific activity of the detector foil with respect to its radial symmetry and counter efficiency which is also a function of radial position.

$$\overline{SA}_{\text{observed}} = \{SA(R)\} \times \{\epsilon(r)\}$$

Counter efficiency measurements with a Cs-137 pin point source were made by R. A. Bennett⁽¹⁵⁾ to determine the relative efficiency of the counter as a function of distance between the pin-point source and the center of the surface of the scintillation crystal.

The quadrant and sector foils used in the fuel rod and tube respectively, were dissected into small annular regions. By super position of the annular regions on the counter efficiency topographical plot, an effective counter efficiency for each region is obtained,

$$\epsilon_R = \frac{\int_r (r) dA}{\int_r dA}$$

where ϵ_R = counter efficiency at a distance r from the center of the surface of the crystal

dA = element of area on the foil at a distance r from the center of the crystal.

Each section of the dissected foil was counted in the position that it would normally assume had the whole foil been placed on the crystal. The corrected activity for that dissected piece is

$$SA_R \text{ (corrected)} = \frac{SA_R \text{ (observed)}}{\epsilon_R}$$

D. Flux Enhancement by Detectors

Three dimensional Monte Carlo calculations by F. E. Dunn⁽⁹⁾ explicitly including foils have indicated that the flux in a foil is often considerably different from the flux in the medium in which it is placed, even for optically thin foils in which no such effect would be expected. A correction must be applied to the measured foil activities to obtain the proper flux averages to be used in determining the thermal disadvantage factors.

The derivation for the fraction of the measured foil activity that is due to flux peaking in a flat foil of thickness t , and diameter or width L , was reported in reference (9) and is summarized as follows:

If a foil of macroscopic absorption cross section Σ_{medium} and a group of neutrons have a path length (l_o) through the foil, then their contribution to the activation of the foil, A_{foil} , is $l_o \Sigma_{\text{foil}}$. The fractional flux peaking in the foil is $l_o (\Sigma_{\text{medium}} - \Sigma_{\text{foil}})$ if $l_o \Sigma_{\text{foil}}$ and $l_o \Sigma_{\text{medium}}$ are small compared to 1. Therefore if A_o is the activation that would occur if the flux in the foil were the same as the flux in the medium,

$$\frac{A_{\text{foil}} - A_o}{A_{\text{foil}}} = \frac{\int l_o (\Sigma_{\text{medium}} - \Sigma_{\text{foil}}) l_o \Sigma_{\text{foil}} f(l_o) dl_o}{\int l_o \Sigma_{\text{foil}} f(l_o) dl_o}$$

where $f(l_o)$ is the probability of the occurrence of l_o . If θ is the angle of incidence between the neutron path and the foil surface, then

$$l_o = \frac{\tau}{\sin \theta}, \text{ for } \theta > \frac{\tau}{L}$$

For an isotropic flux, neglecting edge effects

$$f(l_o) dR_o = \sin \theta \cos \theta d\theta$$

so that the result gives:

$$\frac{A_{\text{foil}} - A_o}{A_{\text{foil}}} = \tau (\Sigma_{\text{medium}} - \Sigma_{\text{foil}}) \ln (L/\tau)$$

The sub-cadmium activities of 0.010 inch thick copper foils were corrected by the use of this equation derived with average cross sections calculated by THERMOS⁽¹⁰⁾.

E. Central Cell End Effects

When the central cell is removed from the test lattice in the course of obtaining the null reactivity measurements, both the front and rear end buffers have one end of their process tubes exposed to the central cell cavity. This exposure could affect the reactivity measurement of the cell-out conditions if there is sufficient neutron streaming to these ends. Therefore, the effects were partially measured during this experiment and correlated with three dimensional calculations from the computer code DOTSN⁽¹⁶⁾ to derive corrections for the measured data.

The measurement of the end effects was based on the fact that decreasing the length of the supercell will increase the solid angle of the central cavity seen by the exposed

portion of the end buffer. The end buffer was switched with the center cell during one of the reactivity measurements in order to determine the reactivity affect of the cavity as a function of its length.

Reactivity worths of copper (14.538 gm/inch of center cell for the short cell and 20.518 gm/inch for the normal test cell) were obtained and used with the DOTSN calculations to extrapolate to the actual effect of the neutron streaming on the infinite multiplication factor measurements. The corrections which were applied to the measured k_{∞} values are listed as follows:

TABLE XIX.   *Corrections to k_{∞} for Cell End Effects*

<u>Cell Conditions</u>	<u>k_{∞} Correction</u>
Normal coolant	- 2.85
Simulated process channel flooding	- 9.90
Simulated process channel and gas vent flooding	- 10.90
Actual water flooding	- 5.80
Dry cell	- 11.73

14. D. F. Newman, "PCTR Measurement of k for Uranium Lithium Supercell," BNWL-622, December 20, 1967.
15. R. A. Bennett, Private Communication.
16. F. R. Mynatt, "Users Manual for DOT," K-1694.

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