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HIGHLY ENRICHED U-AL, 0.95 wt% ENRICHED
URANIUM, AND LI-AL TARGET SUPERCELL -
PCTR EXPERIMENTS

July 1969

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HIGHLY ENRICHED U-AL, 0.95 wt% ENRICHED URANIUM,
AND LI-AL TARGET SUPERCELL - PCTR EXPERIMENTS

By

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July 1969

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ABSTRACT

A highly enriched uranium-aluminum, 0.95 wt% enriched uranium, and lithium-aluminum target supercell lattice has been investigated in the Physical Constants Testing Reactor (PCTR). Neutron multiplication factors, utilization ratios, fast fission factors, resonance escape probabilities, and absorption ratios for ^{238}U and ^6Li relative to ^{235}U have been inferred from null reactivity experiments and measurements of the spatial distributions of neutron reaction rates. Microscopic neutronic parameters (p^{28} , δ^{28} , δ^{25} , $\delta^{6\text{Li}}$, and C^*) measured in the supercell lattice are reported. Experiments were performed at room temperature in a graphite moderated six-by-six cell array placed in the cavity of the PCTR, both with and without light water in the supercell lattice coolant channels.

I. INTRODUCTION

The neutronic characteristics of a graphite lattice, loaded with three different types of elements in a supercell pattern, have been inferred or measured directly in experiments conducted in the Physical Constants Testing Reactor (PCTR). The results of experiments performed in the PCTR at room temperature serve as a benchmark to which theoretical models can be compared for the development of calculation methods.

This report describes the development of techniques and experimental measurements utilizing the PCTR to determine the neutronic parameters for a supercell lattice. Techniques developed in a previous supercell experiment utilizing enriched uranium fuel and lithium-aluminum target in a three-to-one ratio^(1,2) have been extended to analyze the neutronic characteristics of a supercell containing two different types of fuel elements and a target element.

II. SUMMARY

The neutronic characteristics of a 7.5 inch pitch graphite supercell lattice have been determined from experiments performed at room temperature in the PCTR. Each supercell in the test lattice consisted of two columns of 7 wt% uranium (93% ^{235}U) in aluminum fuel rods and one column of 0.95 wt% enriched uranium fuel tubes per column of 2.93 wt% lithium (42.8 at% ^6Li) in aluminum target rods. Experiments were performed with the water coolant channels both wet and dry to obtain values for the change in reactivity and variation of other neutronic characteristics due to coolant loss.

Results of these experiments include values of the infinite medium neutron multiplication factors, associated $1/v$ and thermal utilizations in the fuel and target, fast fission effect, ^{238}U resonance escape probability,

and absorption ratios for ^{238}U and ^6Li relative to ^{235}U . The microscopic neutronic parameters (ρ^{28} , δ^{28} , δ^{25} , $\delta^{6\text{Li}}$, and C^*) measured in the supercell lattice are also reported. The spatial distributions of neutron reaction rates in copper-63 have been measured in the central supercell of the test lattice. Descriptions are presented of the experiments and some of the techniques (most are reported elsewhere, as referenced).

Values of the neutronic characteristics of the supercell lattice are presented in Table I. All results are completely corrected for end effects and known small systematic errors. All uncertainties are standard deviations accumulated by the law of propagation of statistical errors. Considerable data, beyond that summarized in Table I, have been collected and are presented in the body of the report.

TABLE I
Summary of Neutronic Characteristics
Macroscopic Lattice Parameters

Coolant Channel Condition	Wet		Dry	
Lattice Atmos.	Air	Vacuum	Air	Vacuum
k_{∞}	$1.0084 \pm .0017$	$1.0118 \pm .0017$	$1.0041 \pm .0017$	$1.0074 \pm .0017$
$f_{1/v}$	$0.543 \pm .004$	$0.545 \pm .004$	$0.537 \pm .004$	$0.539 \pm .004$
$t_{1/v}$	$0.349 \pm .005$	$0.351 \pm .004$	$0.388 \pm .005$	$0.389 \pm .005$
f_{th}	$0.569 \pm .004$	$0.571 \pm .004$	$0.568 \pm .004$	$0.570 \pm .004$
t_{th}	$0.316 \pm .005$	$0.317 \pm .005$	$0.350 \pm .004$	$0.351 \pm .005$
ϵ	$1.015 \pm .001$		$1.013 \pm .001$	
p^{238}	$0.962 \pm .001$		$0.955 \pm .001$	
$\Sigma_c^{238}/\Sigma_a^{235}$	$0.177 \pm .005$		$0.182 \pm .005$	
$\Sigma_a^{6Li}/\Sigma_a^{235}$	$0.712 \pm .026$		$0.785 \pm .029$	
<u>Microscopic Lattice Parameters</u>				
δ^{28}	$0.027 \pm .002$		$0.023 \pm .002$	
ρ^{28}	$0.693 \pm .014$		$0.852 \pm .017$	
δ^{25}	$0.068 \pm .002$		$0.083 \pm .002$	
C^*	$0.212 \pm .006$		$0.218 \pm .006$	
δ^{6Li}	$0.226 \pm .006$		$0.263 \pm .007$	

Change in Reactivity Due to Coolant Loss

$$\frac{\Delta k \text{ (Wet} \rightarrow \text{Dry)}}{k_{\infty} \text{ (Wet)}} - .0043 \pm .0024 \text{ (Air)} - .0044 \pm .0024 \text{ (Vacuum)}$$

III. DESCRIPTION OF THE EXPERIMENT

A. Test Lattice Inserted into PCTR Cavity

The PCTR has a 41.25 inch x 41.25 inch x 37.5 inch cavity into which test lattices are placed. The test lattice in this experiment consisted of a 6x6 array of 7.5 inch pitch graphite cells loaded with 18 columns of 7 wt% uranium (93% ^{235}U) in aluminum fuel rods, 9 columns of 0.95 wt% enriched uranium fuel tubes, and 9 columns of 2.93 wt% lithium (42.8 at% Li^6) in aluminum target rods, as shown in Figure 1. Null reactivity measurements were made with the four center cells (referred to as the central supercell). The central supercell of the test lattice is square shaped, having eight cell surfaces exposed to the radial buffer cells. The void formed by removal of the central supercell exposes four surfaces of U-Al cells, two surfaces of 0.95% U cells, and two surfaces of Li-Al cells (precisely the 2:1:1 ratios). As shown in Reference 2, the square shaped central supercell is typical of an infinite array of such supercells.

E = 7 wt. % Uranium (93% ^{235}U) in Aluminum Fuel

U = 0.95 wt. % Enriched Uranium Metal Fuel

T = Lithium in Aluminum Target

FIGURE 1
(6 x 6 Test Cell Array)
PCTR Core Fuel Loading Diagram

B. Central Supercell Description

The cells comprising the supercell can be further distinguished by their geometrical relation to the target cells. The two U-Al cells each have one cell surface adjacent to a target cell and one cell surface adjacent to a 0.95% U cell; the other two cell surfaces are adjacent to U-Al cells. These highly enriched U-Al cells will be referred to as "E" cells. The 0.95 wt% enriched uranium cell, referred to as "U" cells, has two cell surfaces adjacent to target cells and two cell surfaces adjacent to E cells. The lithium-aluminum target cell, referred to as "T" cell, has two cell surfaces adjacent to E cells and two cell surfaces adjacent to U cells. The characteristic neutron spectrum and the neutron absorption rates of these cell types were different so that in an experiment involving such a supercell, relative absorption rates in each cell type were required simultaneously in order to determine the effect of adjacent cell interactions.

C. Geometry and Composition of Each Type Cell

A 21.875 inch long supercell was used as a typical sample of the test lattice to permit neutron spectrum buffering in the axial direction as well as the radial direction. Details of the composition and dimensions of the highly enriched uranium-aluminum (E) central cells are listed in Table II; central lithium-aluminum target (T) cell details are listed in Table III; and the details for the 0.95 wt% enriched uranium tubular fuel (U) cell are listed in Table IV. The masses of each material reported in Tables II, III, and IV were obtained by weighing the materials in each 21.875 inch long central cell, and by using isotopic analyses made on each type of fuel and target material. Extensive measurements were made both

with the coolant channels filled with water, and with the coolant channels filled with air. Neutronic characteristics of the test lattice in each condition were determined from experimental measurements.

TABLE II

Composition and Geometry of the Wet Uranium-Aluminum Fuel
Central Cell

Region			Outside Radius	Density		21.875" Center Cell	
Name	No.	Isotope	cm	gm/cm ³	nuclei cm ³ x10 ⁻²⁴	Mass, gm	Volume, cm ³
Fuel	1		1.697	2.9014 (a) (b)		1458.183	502.7
		²³⁵ U		0.18856	4.8311x10 ⁻⁴	94.787	
		²³⁸ U		0.01116	2.823x10 ⁻⁵	5.609	
		²³⁴ U		0.00210	5.404x10 ⁻⁶	1.054	
		Al		2.699	6.0244x10 ⁻²	1356.733	
Clad	2	Al	1.848	2.699	6.0244x10 ⁻²	229.62	85.1
Water	3		2.187	0.9955		245.49	247.2
		H		0.1113	6.6568x10 ⁻²	27.539	
		O		0.8842	3.3284x10 ⁻²	218.562	
Process Tube	4	Zr	2.287	6.400	4.2254x10 ⁻²	499.20	78.0
Void	5		2.338	1.209x10 ⁻³		0.04981	41.2
		N		9.2554x10 ⁻⁴	3.9794x10 ⁻⁵	0.03813	
		O		2.8361x10 ⁻⁴	1.0676x10 ⁻⁵	0.01168	
Graphite	6		10.747 (c)	1.6082		30888.1	19206.6
		C		1.6079	8.0463x10 ⁻²	30881.4	
		N		2.6543x10 ⁻⁴	1.1412x10 ⁻⁵	5.0984	
		O		8.1336x10 ⁻⁵	3.0617x10 ⁻⁶	1.5623	

(a) Reduced density to account for fuel element end caps.

(b) Density of 93% enriched uranium-aluminum core is 2.9152 gm/cm³.

(c) Cylindricized radius.

TABLE III

Composition and Geometry of the Wet Lithium-Aluminum Target
Center Cell

Region			Outside Radius	Density		21.875" Centercell	
Name	No.	Isotope	cm	gm/cm ³	$\frac{\text{nuclei}}{\text{cm}^3} \times 10^{-24}$	Mass, gm	Volume, cm ³
Target	1	⁶ Li	1.907	2.46996		(a) (b) 1567.987	634.9
		⁷ Li		0.02697	2.70035×10^{-3}	17.1235	
				0.04205	3.60646×10^{-3}	26.6947	
		Al		2.40064	5.3418×10^{-2}	1524.1688 ^(a)	
Clad	2	Al	2.032	2.699	6.0244×10^{-2}	231.844	85.9
Water	3		2.187	0.9955		113.6957	114.2
		H		0.1113	6.6568×10^{-2}	12.7227	
		O		0.8842	3.3284×10^{-2}	100.973	
Process Tube	4	Zr	2.287	6.400	4.2254×10^{-2}	499.20	78.0
Void	5		2.338	1.209×10^{-3}		0.04981	41.2
		N		9.2554×10^{-4}	3.9794×10^{-5}	0.03813	
		O		2.8361×10^{-5}	1.0676×10^{-5}	0.01168	
Graphite	6		10.747 (c)	1.6082		30888.1	19206.6
		C		1.6079	8.0463×10^{-2}	30881.4	
		N		2.6543×10^{-4}	1.1412×10^{-5}	5.0984	
		O		8.1336×10^{-5}	3.0617×10^{-6}	1.5623	

(a) Includes aluminum end caps on target elements = 72.487 gm.

(b) Mass of target core material is 1495.5 gm.

(c) Cylindricized radius.

TABLE IV

Composition and Geometry of the Wet 0.95 wt% Enriched Uranium Fuel
Central Cell

Region			Outside Radius	Density		21.875" Center Cell	
Name	No.	Isotope	cm	gm/cm ³	$\frac{\text{nuclei}}{\text{cm}^3} \times 10^{-24}$	Mass, gm	Volume, cm ³
Water	1		0.555	0.9955		53.5250	53.8
		H		0.1113	6.6568×10^{-2}	5.9843	
		O		0.8842	3.3284×10^{-2}	47.5408	
Clad	2	Al	0.692	2.699	6.0244×10^{-2}	80.4626	29.8
Fuel	3		1.803	16.799(a) (b)		8130.677	484.0
		²³⁵ U		0.1560	3.9969×10^{-4}	75.499	
		²³⁸ U		16.290	4.1209×10^{-2}	7884.331	
		Al		0.353	7.879×10^{-3}	170.847	
Clad	4	Al	1.916	2.699	6.0244×10^{-2}	197.960	73.3
Water	5		2.187	0.9955		193.2266	194.1
		H		0.1113	6.6568×10^{-2}	21.6033	
		O		0.8842	3.3284×10^{-2}	171.6232	
Process Tube	6	Zr	2.287	6.400	4.2254×10^{-2}	499.200	78.0
Void	7		2.338	1.209×10^{-3}		0.04981	41.2
		N		9.2554×10^{-4}	3.9794×10^{-5}	0.03813	
		O		2.8361×10^{-4}	1.0676×10^{-5}	0.01168	
Graphite	8		10.747(c)	1.6082		30888.1	19206.6
		C		1.6079	8.0463×10^{-2}	30881.4	
		N		2.6543×10^{-4}	1.1412×10^{-5}	5.0984	
		O		8.1336×10^{-5}	3.0617×10^{-6}	1.5623	

(a) Reduced density to account for fuel element end caps.

(b) Density of 0.95 wt% enriched uranium core is 18.92 gm/cm^3 .

(c) Cylindricized radius.

IV. EXPERIMENTAL TECHNIQUES AND RESULTS

A. The PCTR Method for Determining k_{∞}

Since the Physical Constants Testing Reactor first went critical in October of 1955, many different types of experiments on various lattices have been performed. A frequent application of the reactor is the measurement of the infinite medium neutron multiplication factor (k_{∞}) for test lattices. The general techniques are well documented⁽³⁾ for measurements performed on single cells. A summary of the method for measuring k_{∞} of a reactor lattice will be given to allow a clearer understanding of the specific experiments presented in this report.

There are three related parts in a k_{∞} measurement in the PCTR:

1. The neutron energy distribution in the central test cell is adjusted so that it is identical to that which would be present in an infinite array of test cells.
2. The mass of neutron absorber (copper) required to absorb all the excess neutrons of the central test cell is accurately measured in the central cell having the proper neutron energy distribution, obtained in Part 1.
3. The relative reaction rates of the test cell components are measured in both the lattice poisoned to unit multiplication and the unpoisoned lattice when the proper neutron energy distribution exists in the test cell.

B. Neutron Energy Distributions in the Lattices

The neutron energy distribution is usually inferred by measuring cadmium ratios of resonance detectors, and the proper cadmium ratio is

determined by comparisons of ratios between the central test cell and surrounding cells at equivalent positions within each cell. One of the most useful materials for such measurements is gold which, when covered with cadmium, is activated almost entirely by neutrons in a narrow region around 4.9 ev. The use of this technique at intermediate energies is not at all complicated, but the use of a large number of foils having slightly different thicknesses made it necessary to correct the measured gold cadmium ratios to a standard foil thickness gold cadmium ratio using experimental data published by R. A. Bennett.⁽⁴⁾

Gold foils approximately 1/2 inch in diameter and 0.005 inches thick were irradiated bare and in 0.040 inch thick cadmium covers to obtain cadmium ratios from which neutron energy distributions could be inferred. The foils were placed on a radius approximately 1.75 in. away from the center of both fuel and target cells so that reasonable changes in the spectrum could be measured. Generally, the objective was to match the spectrum of all three cell types in the radial buffer region of the test lattice (i.e., E, U, and Target) so that each type would have the same cadmium ratio as the center cell of the same type. For the 6x6 test array (see Figure 1) the following comparisons were made in the determination of a spectrum match:

<u>Cell Type</u>	<u>Center Cell</u>	<u>Equivalent Radial Buffer Cells</u>
E	16 and 22	10, 28, 14, 20, 8, 26
U	21	9, 17, 29
T	15	27, 23, 11

Specifically, a weighted average of the (gold cadmium ratio -1) of the equivalent radial buffer cells, in the first row of cells surrounding the central cells, was calculated for comparison with the (gold cadmium ratio -1)

of the corresponding central cell. The weighting factor used is proportional to the inverse of the linear distance, center-to-center, from a radial buffer cell to the nearest center cell of the same type. Thus, the average neutron spectral indicator of a single type of radial buffer cell is defined as:

$$\overline{(\text{CdR}-1)} = \frac{\sum W_i (\text{CdR}-1)_i}{\sum W_i} \quad (1)$$

where $(\text{CdR}-1)_i$ is the (gold cadmium ratio -1) of the i^{th} radial buffer cell of a particular type, and W_i is its weighting factor. This average neutron spectral indicator for the radial buffer cells of a particular type is compared to the (gold cadmium ratio -1) measured in the central cell of the same type to determine the spectral mismatch. The difference between $(\text{CdR}-1)$ measured in the center cell and the average radial buffer value, $\overline{(\text{CdR}-1)}$, measured in the first row of cells surrounding the central cells, is referred to as ΔE , ΔU , and ΔT for cell types E, U, and T, respectively. The criteria for obtaining matched spectral conditions, therefore, is when ΔE , ΔU , and ΔT simultaneously approach zero. Variation in the spectral mismatch for each type cell was accomplished by changing the positions of the PCTR driver fuel columns, by the insertion of Lucite rods between the PCTR driver fuel and the test lattice, and by changing the axial position of the PCTR flux leveling fuel. The properly matched spectral conditions were obtained in the central supercell for each lattice condition by experimental iteration.

C. Null Reactivity Measurements

The mass of neutron absorber required to absorb the excess neutrons produced by the test cell is determined by a null reactivity technique.

This technique forms the basis for the PCTR measurement and depends upon the observation that a properly poisoned test cell will have the same reactivity effect on the reactor as an empty cavity. In a properly poisoned cell the neutron absorptions balance the neutron productions. The central supercell which was the test cell for the null reactivity measurements is shown being removed from the 6x6 test array in Figure 2. Short end buffer cells enclose the central supercell along the long axis. Slots are provided in the lattice and on the central supercell for insertion of copper poison strips at the cell boundaries.

A reactivity series was obtained for each reactor loading for which gold cadmium ratios were measured. A reactivity series consisted of measuring the reactivity of the lattice in four configurations: ρ cell-in; ρ cell-out, ρ cell-out with copper in the cavity; and, ρ cell-in with copper on the boundary. From these measurements the reactivity worth of three quantities are obtained:

1. The worth of the central supercell, $\Delta\rho_{\text{cell}} = \rho_{\text{cell-in}} - \rho_{\text{cell-out}}$.
2. The worth of a small increment of copper on the cell boundary,

$$\Delta\rho_{\text{Cu}}^{\text{boundary}} = \rho_{\text{cell-in}} - \rho_{\text{cell-in with copper on the boundary}}$$

3. The worth of a small increment of copper in the cavity,

$$\Delta\rho_{\text{Cu}}^{\text{cavity}} = \rho_{\text{cell-out}} - \rho_{\text{cell-out with copper in the cavity}}, \text{ which}$$

is vacated by the central supercell when it is out of the reactor.

These three quantities were combined to calculate the amount of copper that must be added to or subtracted from the test cell so that the null reactivity condition could be satisfied.

FIGURE 2

Central Supercell Loading in PCTR Experimental Lattice
6x6 Test Cell Array

An estimate of the mass of copper (M_j) required to absorb the excess neutrons of the central supercell was obtained for each gold cadmium ratio measurement, (j), from the equation:

$$M_j = \left(\frac{\Delta\rho_{\text{cell}} - \Delta\rho_{\text{N}_2}}{\Delta\rho_{\text{Cu}}^{\text{boundary}}} \right)_j M_{\text{Cu}}^{\text{boundary}} \quad (2)$$

where $M_{\text{Cu}}^{\text{boundary}}$ = the mass of the small increment of copper inserted at the boundary of the central supercell in the ρ_{cell} -in with copper on the boundary measurement; $\Delta\rho_{\text{N}_2}$ = the reactivity worth of the nitrogen in the air which is present in the cavity vacated by the central supercell when it is out of the reactor (see VI-A, "Nitrogen Corrections"). It is readily apparent that the reactivity worth of the central supercell, and hence the mass of copper required to absorb the excess neutrons of the test cell, will change as a function of the neutron energy distribution in the supercell. Because it is impractical to achieve an exact matched spectrum loading, several measurements are made which bracket the desired match and converge toward it. The correct mass of copper $(M_o)^{\text{Cu}}$ required to achieve unit multiplication is then interpreted as a function of the central supercell spectral mismatch in each type cell.

$$(M_o)^{\text{Cu}} = M_j^{\text{Cu}} + \frac{\partial M^{\text{Cu}}}{\partial T} \Delta T_j + \frac{\partial M^{\text{Cu}}}{\partial U} \Delta U_j + 2 \frac{\partial M^{\text{Cu}}}{\partial E} \Delta E_j \quad (3)$$

The mass of copper, $(M_j)^{\text{Cu}}$, required to absorb the excess neutrons of the central supercell in the j^{th} slightly mismatched neutron spectrum was measured along with the spectral mismatch indicators, ΔT_j , ΔU_j , and ΔE_j in at least four different experimental loadings. The four simultaneous

equations, of the form of equation (3), can be solved for the four unknown quantities: $(M_O)^{Cu}$; $\frac{\partial M^{Cu}}{\partial T}$; $\frac{\partial M^{Cu}}{\partial U}$; and $\frac{\partial M^{Cu}}{\partial E}$. The correct mass of copper $(M_O)^{Cu}$, required to achieve unit multiplication in the equilibrium neutron spectrum of the supercell lattice was used to infer the infinite medium neutron multiplication factor in the unpoisoned lattice, when combined with relative reaction rate measurements in all central supercell components.

D. Relative Reaction Rate Measurements

Relative reaction rates of the test cell components are determined from foil activation measurements. Energy dependences of the reaction rates are determined from cadmium ratios. Bare and cadmium covered foils were activated in separate irradiations, and normalization between irradiations was accomplished by placing monitor foils in an external thermal column.⁽⁵⁾

The relative reaction rates of the supercell components were determined in loadings where the gold cadmium ratio data indicated that the neutron spectrum had the proper energy distribution. Copper foils (0.010" thickness) were used for traverses in the graphite, in the fuel, in the target, and in the coolant channels. Foil locations in the central supercell graphite, shown in Figure 3, are sufficiently provided so that two dimensional plots of relative reaction rates can be made.

The specific activities of the copper foils placed in the graphite relative to the foil in the external thermal column are presented in Table V. Specific activities of copper foils placed in the fuel, in the target, and in the coolant channels relative to foils in the external thermal column are presented in Table VI. The activities were calculated using a revised version of the computer code APDAC-I,⁽⁶⁾ which corrects the counting data

for activity decay during counting, room background, foil mass variations, and residual activity. Spatial variation of the sub-cadmium and epi-cadmium relative copper-63 activities along radial traverses at various angles in the wet central supercell are shown in Figures 4 through 7. The axial variation of the sub-cadmium relative copper-63 activities in the wet central supercell are shown in Figures 8 through 10.

FIGURE 3
Foil Locations in the Central Supercell Graphite

TABLE V

Relative Activities of Copper Foils in Central Supercell Graphite

Traverse Position	Radius in.	Wet Lattice		Dry Lattice	
		Specific Activity		Specific Activity	
		Sub-Cd	Epi-Cd	Sub-Cd	Epi-Cd
Ref.*		1.000	1.000	1.000	1.000
r ₁	3.750	5.822	0.302	4.980	0.352
r ₂	2.420	5.753	0.307	4.795	0.361
r ₃	1.000	4.988	0.302	3.656	0.363
r ₄	1.000	4.839	0.308	3.647	0.370
r ₅	2.420	5.489	0.319	4.603	0.377
r ₆	3.750	5.398	0.305	4.604	0.353
r ₇	2.420	4.905	0.282	4.076	0.321
r ₈	1.000	3.202	0.247	2.290	0.286
r ₉	1.170	3.598	0.257	2.749	0.296
r ₁₀	1.670	4.315		3.526	
r ₁₁	2.170	4.754	0.285	3.975	0.328
r ₁₂	2.670	5.075		4.304	
r ₁₃	3.170	5.302	0.300	4.387	0.354
r ₁₄	3.670	5.496		4.671	
r ₁₅	4.230	5.620	0.313	4.869	0.369
r ₁₆	3.670	5.688		4.864	
r ₁₇	3.170	5.671	0.320	4.819	0.372
r ₁₈	2.670	5.628		4.737	
r ₁₉	2.170	5.547	0.316	4.597	0.372
r ₂₀	1.670	5.378		4.331	
r ₂₁	1.170	5.113	0.315	3.894	0.379
r ₂₂	1.170	5.067	0.317	3.900	0.382
r ₂₃	1.670	5.412		4.374	
r ₂₄	2.170	5.626	0.320	4.655	0.383
r ₂₅	2.670	5.756		4.836	
r ₂₆	3.170	5.839	0.322	4.958	0.388
r ₂₇	3.670	5.885		5.021	
r ₂₈	4.230	5.880	0.323	5.025	0.388
r ₂₉	1.170	3.358	0.251	2.645	0.294
r ₃₀	1.670	4.134		3.428	
r ₃₁	2.170	4.621		3.911	
r ₃₂	2.670	4.945	0.282	4.253	0.330
r ₃₃	3.170	5.238		4.531	
r ₃₄	3.670	5.422		4.687	
r ₃₅	4.170	5.563	0.297	4.837	0.348
r ₃₆	4.170	5.759	0.294	4.969	0.381
r ₃₇	3.670	5.699		4.897	
r ₃₈	3.170	5.643		0.439	
r ₃₉	2.670	5.534	0.288	4.725	0.337
r ₄₀	2.170	5.408		4.520	
r ₄₁	1.670	5.179		4.239	
r ₄₂	1.170	4.817	0.269	3.767	0.316

TABLE V(Con't)

Traverse Position	Radius in.	Wet Lattice		Dry Lattice	
		Specific Activity		Specific Activity	
		Sub-Cd	Epi-Cd	Sub-Cd	Epi-Cd
r ₄₃	1.170	4.709	0.271	3.676	0.310
r ₄₄	1.670	5.131		4.204	
r ₄₅	2.170	5.391	0.279	4.526	0.318
r ₄₆	2.670	5.578		4.733	
r ₄₇	3.170	5.681	0.286	4.876	0.324
r ₄₈	3.670	5.784		4.982	
r ₄₉	4.230	5.856	0.289	5.031	0.329
r ₅₀	1.750	4.220	0.269	3.519	0.348
r ₅₁	2.250	4.643		3.944	
r ₅₂	2.750	4.950		4.231	
r ₅₃	3.250	5.199		4.468	
r ₅₄	3.750	5.315	0.289	4.576	0.330
r ₅₅	3.250	5.379		4.621	
r ₅₆	2.750	5.386		4.595	
r ₅₇	2.250	5.097		4.468	
r ₅₈	1.750	5.121	0.278	4.262	0.325
r ₅₉	1.750	5.425	0.316	4.426	0.378
r ₆₀	2.250	5.645		4.690	
r ₆₁	2.750	5.795		4.849	
r ₆₂	3.250	5.855		4.958	
r ₆₃	3.750	5.894	0.318	4.975	0.381

* External thermal column (bare foils)

TABLE VI

Relative Activities of Copper Foils in All Cell Components

Cell	Material	Wet Lattice		Dry Lattice	
		Specific Activity		Specific Activity	
		Sub-Cd	Epi-Cd	Sub-Cd	Epi-Cd
E	Fuel	2.835	0.314	2.691	0.398
	Cladding	3.549	0.317	3.389	0.376
	Coolant	4.455	0.320	3.583	0.377
	Process	5.051	0.310	3.673	0.378
	Tube				
	Air Gap	5.134	0.310	3.671	0.378
	Graphite	5.684	0.320	5.383	0.382
U	Inner	2.877	0.241	2.032	0.283
	Coolant				
	Inner	2.349	0.250	1.972	0.300
	Cladding				
	Fuel	2.421	0.264	2.178	0.315
	Outer	3.099	0.264	2.845	0.320
	Cladding				
	Outer	3.768	0.265	2.992	0.321
	Coolant				
	Process	4.256	0.270	3.101	0.322
	Tube				
	Air Gap	4.425	0.270	3.260	0.322
	Graphite	5.523	0.287	4.680	0.349
T	Target	0.457	0.206	0.468	0.244
	Cladding	1.929	0.220	1.988	0.260
	Coolant	2.500	0.230	2.186	0.270
	Process	3.012	0.240	2.276	0.275
	Tube				
	Air Gap	3.319	0.240	2.279	0.275
	Graphite	5.072	0.294	4.257	0.344

FIGURE 4
Cylindricized Radial Traverse Between LiAl Target and
Uranium-Aluminum Fuel Cell
Wet Lattice

FIGURE 5
Horizontal Radial Traverse Between Uranium-Aluminum Fuel
Cell and LiAl Target Cell
Wet Lattice

FIGURE 6
Vertical Traverse Between Target and 0.95% Enriched U Cell
Wet Lattice

FIGURE 7
Radial Traverse in Graphite Between LiAl Target and 0.95%
Enriched Uranium Cells @ 45° Angle
Wet Lattice

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FIGURE 8
Axial Relative Reaction Rate Traverses in the Target Cell - Wet 2(E):(U):(T)
Supercell

FIGURE 9
Axial Relative Reaction Rate Traverses in Uranium-Aluminum (E) Cell - Wet
2(E):(U):(T)
Supercell

FIGURE 10
Axial Relative Reaction Rate Traverses in the 0.95% Enriched Uranium (U) Cell -
Wet 2(E):(U):(T)
Supercell

FIGURE 11
Cylindricized Radial Traverse Between LiAl Target and
Uranium-Aluminum Fuel Cell
Dry Lattice

FIGURE 12
Horizontal Radial Traverse Between Uranium-Aluminum Fuel
Cell and LiAl Target Cell
Dry Lattice

FIGURE 13
Vertical Traverse Between Target and 0.95% Enriched U Cell
Dry Lattice

FIGURE 14
Radial Traverse in Graphite Between LiAl Target and 0.95%
Enriched Uranium Cells @ 45° Angle
Dry Lattice

FIGURE 15
Axial Relative Reaction Rate Traverses in the Target Cell - Dry 2(E):(U):(T)
Supercell

FIGURE 16
Axial Relative Reaction Rate Traverses in Uranium-Aluminum (E) Cell - Dry
Supercell
 $2(E):(U):(T)$

FIGURE 17
Axial Relative Reaction Rate Traverses in the 0.95% Enriched Uranium (U) Cell -
Dry 2(E) : (U) : (T)
Supercell

Similarly, the spatial variation of the relative copper-63 activities measured in the dry lattice's central supercell are shown in Figures 11 through 17.

The measured spatial distributions of the relative reaction rates in copper-63, $SA^{63}(r)$, were corrected for non-1/v absorption rates. Non-1/v corrections were inferred from copper-63 cadmium ratio measurements and resonance integral data.⁽⁴⁾

$$SA_{1/v}^{63}(r) = SA_{total}^{63}(r) - SA_{epi-Cd}^{63}(r) \left(\frac{RI_{ex}}{RI_{epi-Cd}} \right) \quad (4)$$

where, RI_{ex} = effective excess resonance integral for copper-63 in a 0.010" thick foil, 1.63073 barns;

RI_{epi-Cd} = effective total epi-cadmium resonance integral for copper-63 in a 0.010" thick foil, 3.42011 barns.

The spatial distributions of the 1/v neutron reaction rates in each region of the central supercell are required for the determination of the 1/v utilization in all supercell components.

E. Neutron Cross Section Generating Technique

Experimentally determined boundary conditions were utilized in transport theory calculations for generation of spectrum averaged cross sections. Two-dimensional plots of the sub-cadmium neutron reaction rate in copper-63 were obtained from experimental data presented in Table V. Radial sub-cadmium activation traverses at various angles between adjacent cells of the central supercell were plotted to determine the radial location of the zero-gradient thermal flux boundary at each angle. A graphical representation of the zero-gradient thermal flux boundary contours was obtained by cross plotting the location of the boundary along each radial traverse on a single graph

representing the cross section of the central supercell. The cross sectional area inside the zero-gradient thermal flux boundary contour was cylindricized for each type cell in the central supercell. The effect of water coolant loss on the equivalent cylindricized cell radii, and a comparison with the actual cell physical radius, are shown in Table VII.

TABLE VII

Effect of Water Coolant Loss on the Equivalent Cylindricized Cell Radii

<u>Cell Type</u>	<u>Equivalent Cylindricized Radius, cm</u>	
	<u>Wet Coolant Channels</u>	<u>Dry Coolant Channels</u>
Li-Al Target, (T)	12.639	11.887
0.95 % Enriched Uranium, (U)	10.300	10.414
7 wt% Uranium (93% enriched) in Aluminum, (E)	9.907	10.284
Physical Boundary	10.747	10.747

The graphical representations of the zero-gradient thermal flux boundary contours are shown in Figure 18 for the wet supercell lattice and in Figure 19 for the dry supercell lattice.

Thermal neutron spectrum averaged microscopic cross section values, calculated by transport theory, were obtained from computer code THERMOS.⁽⁷⁾ Single cell calculations were made for each type of cell both wet and dry in cylindricized geometry, and a reflecting boundary condition was used at the outer boundary. The location of the outer boundary was obtained from the equivalent cell radius determined experimentally from sub-cadmium zero-gradient neutron flux boundaries.

This technique is considered to be a distinct improvement over the direct use of the Wescott approximation⁽⁸⁾ for calculating effective thermal

cross sections, $\hat{\sigma} = \sigma_0(g + rs)$, wherein one must, in practice, assume both the energy distribution of neutrons and its characteristic spectral indices; e.g., a Maxwellian with an estimated neutron temperature. In general, the cross sections calculated by THERMOS are defined as:

$$\hat{\sigma}(r) = \frac{\int_0^{E_{ec}} \sigma(E) \phi(E, r) dE}{\int_0^{E_{ec}} \sqrt{E_0/E} \phi(E, r) dE}, \quad (5)$$

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.

Region averaged THERMOS cross sections calculated using the previously described technique are presented in Table VIII for the wet lattice, and in Table IX for the dry lattice.

FIGURE 18
Zero Gradient Neutron Flux Contours in the Wet 2E:U:T
Supercell

FIGURE 19
Zero Gradient Neutron Flux Contours in the Dry 2E:U:T
Supercell

TABLE VIII

Thermal Neutron Spectrum Averaged Cross Sections from THERMOS
(Wet Lattice)

Isotope	Region	E-Type Fuel Cell		$\hat{\sigma}_i = \frac{(\bar{\sigma}_a)_i}{(\bar{\sigma}_a 1/v)_i}$
		$\bar{\sigma}_a$	$\bar{\sigma}_{a1/v} \text{ (a)}$	
Al	1	0.153427	0.667072	0.23000
²³⁵ U	1	431.912		647.4743
²³⁸ U	1	1.84426		2.76471
Al	2	0.163067	0.708988	0.23000
H	3	0.245854	0.749554	0.32800
O	3	1.57394×10^{-4}		0.00021
Zr	4	0.136978	0.761006	0.18000
N	5	1.33376	0.762132	1.75000
O	5	1.60035×10^{-4}		0.00021
C	6	2.58926×10^{-3}	0.761547	0.00340
N	6	1.33274		1.75000
O	6	1.59912×10^{-4}		0.00021
<hr/>				
U-Type Fuel Cell				
H	1	0.235401	0.717685	0.32800
O	1	1.50702×10^{-4}		0.00021
Al	2	0.152979	0.665126	0.23000
Al	3	0.152983	0.665144	0.23000
²³⁵ U	3	430.866		647.7785
²³⁸ U	3	1.83944		2.76548
Al	4	1.62286	0.705509	0.23000
H	5	0.242906	0.740568	0.32800
O	5	1.55507×10^{-4}		0.00021
Zr	6	0.135604	0.753373	0.18000
N	7	1.32027	0.754423	1.75000
O	7	1.58416×10^{-4}		0.00021
C	8	2.56676×10^{-3}	0.754930	0.00340
N	8	1.32116		1.75000
O	8	1.58523×10^{-4}		0.00021

(a) $\bar{\sigma}_{a0} = 1.000$

TABLE VIII (Con't)

Isotope	Region	Target Cell		$\hat{\sigma}_i = \frac{(\bar{\sigma}_a)_i}{(\bar{\sigma}_{a1/v})_i}$
		$\bar{\sigma}_a$	$\bar{\sigma}_{a1/v} (a)$	
Li ⁶	1	518.580	0.549344	944.00
Li ⁷	1	0.018283		0.03300
Al	1	0.126349		0.23000
Al	2	0.160900	0.699566	0.23000
H	3	0.239036	0.728769	0.23800
O	3	1.53029×10^{-4}		0.00021
Zr	4	0.133921	0.744019	0.18000
N	5	1.30616	0.746358	1.75000
O	5	1.56723×10^{-4}		0.00021
C	6	2.50142×10^{-3}	0.735712	0.00340
N	6	1.28753		1.75000
O	6	1.54487×10^{-4}		0.00021

TABLE IX

Thermal Neutron Spectrum Averaged Cross Sections from THERMOS (Dry Lattice)

E-Type Fuel Cell

Isotope	Region	$\bar{\sigma}_a$	$\bar{\sigma}_{a1/v}$ (a)	$\hat{\sigma}_i = \frac{(\bar{\sigma}_a)_i}{(\bar{\sigma}_{a1/v})_i}$
Al	1	0.144472	0.628139	0.166320
²³⁵ U	1	403.008		641.590
²³⁸ U	1	1.73936		2.76907
Al	2	0.153498	0.667385	0.23000
N	3	1.18123	0.674972	1.75000
O	3	1.41733×10^{-4}		0.00021
Zr	4	0.122043	0.678032	0.18000
N	5	1.18909	0.679465	1.75000
O	5	1.42676×10^{-4}		0.00021
C	6	2.40615×10^{-3}	0.707692	0.00340
N	6	1.23849		1.75000
O	6	1.48603×10^{-4}		0.00021

U-Type Fuel Cell

N	1	1.06489	0.608491	1.75000
O	1	1.27773×10^{-4}		0.00021
Al	2	0.139140	0.604958	0.23000
Al	3	0.143166	0.622460	0.23000
²³⁵ U	3	398.950		640.925
²³⁸ U	3	1.72418		2.76995
Al	4	0.152996	0.665200	0.23000
N	5	1.17532	0.671598	1.75000
O	5	1.41024×10^{-4}		0.00021
Zr	6	0.121601	0.675574	0.18000
N	7	1.18444	0.676808	1.75000
O	7	1.42118×10^{-4}		0.00021
C	8	2.39961×10^{-3}	0.705769	0.00340
N	8	1.253512		1.75000
O	8	1.48200×10^{-4}		0.00021

(a) $\sigma_{a0} = 1.000$

TABLE IX (Con't)

Isotope	Region	$\overline{\sigma_a}$	$\overline{\sigma_{a1/v}} \quad (a)$	$\hat{\sigma}_i = \frac{(\overline{\sigma_a})_i}{(\overline{\sigma_{a1/v}})_i}$
Li ⁶	1	493.749	0.523039	944.000
Li ⁷	1	0.0172603		0.03300
Al	1	0.120299		0.23000
Al	2	0.155738	0.677120	0.23000
N	3	1.19367	0.682082	1.75000
O	3	1.43226x10 ⁻⁴		0.00021
Zr	4	0.122964	0.683148	0.18000
N	5	1.19522	0.682967	1.75000
O	5	1.43412x10 ⁻⁴		0.00021
C	6	2.35263x10 ⁻³	0.691949	0.00340
N	6	1.21094		1.75000
O	6	1.45298x10 ⁻⁴		0.00021

One may note that as defined in Eq. 5, the values will be 2200 m/sec values unless the cross section is non-1/v for $0 \leq E \leq 0.683$ ev; e.g., see ^{235}U in Tables VIII and IX. These cross sections will be used to infer the relative 1/v absorption rates in all supercell components from experimental copper activation data.

F. Determination of 1/v Utilizations and Thermal Utilizations

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. Experimental values are inferred from measured spatial distributions of the 1/v neutron reaction rate in ^{63}Cu . At space point r , the 1/v absorption rate in ^{63}Cu is given by:

$$\overline{SA}^{63}(r) = c \frac{N_0}{A^{63}} \hat{\sigma}^{63}(r) \int_0^\infty \sqrt{E_0/E} \phi(E,r) dE \quad (6)$$

where, c is a space independent normalizing constant.

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

$$\overline{SA}^x(r) = \left(\frac{\hat{\sigma}^x(r) A^{63}}{\hat{\sigma}^{63}(r) A^x} \right) \overline{SA}^{63}(r) \quad (7)$$

where, A is the atomic weight.

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

$$(\text{Abs})^x = M^x \frac{\int_{\text{all of region } x} SA^x(r) dV}{\int_{\text{all of region } x} dV} \quad (8)$$

where, M^x is the mass of material x in the region.

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

$$f^x = (\text{Abs})^x / \sum_i (\text{Abs})^i \quad (9)$$

Absorption rates for all supercell components and both $1/v$ utilizations and thermal utilizations of these components are presented in Table X for the wet lattice, and in Table XI for the dry lattice.

TABLE X
Absorption Rates, 1/v and Thermal Utilizations (Wet Lattice)

<u>E-Type Fuel Cell</u>							
#	Region	Isotope	Mass	SA ⁶³ _{1/v}	Abs.1/v	SA ⁶³ _{sub-Cd}	Abs.sub-Cd
1	Fuel	Al	1356.733	2.99949	485.1210	2.83529	458.5631
		²³⁵ U	94.7874		10952.4850		10352.8912
		²³⁴ U	1.0535		18.3149		17.3123
		²³⁸ U	5.6087		2.7323		2.5827
2	Fuel Clad	Al	229.62	3.71514	101.6933	3.54929	97.1535
3	Water	H	27.5390	4.62245	579.2815	4.45503	558.3005
		O	218.562		0.1869		0.1801
4	Process Tube	Zr	499.200	5.21351	71.8184	5.05132	69.5841
5	Air	N	0.03813	5.29609	0.3528	5.1339	0.3420
		O	0.01168		0.0000		0.0000
6	Graphite	C	30881.4	5.851959	715.8185	5.68445	695.3289
		N	5.0984		52.1291		50.6370
		O	1.5623		0.0017		0.0017

<u>U-Type Fuel Cell</u>							
1	Water	H	5.9843	3.00304	81.7791	2.87711	78.3497
		O	47.5408		0.0265		0.0253
2	Fuel Inner Clad	Al	80.4626	2.47935	23.7815	2.34855	22.5268
3	Fuel	Al	170.847	2.55858	52.1093	2.42061	49.2993
		²³⁵ U	75.499		7444.9111		7043.4443
		²³⁸ U	7884.331		3277.2321		3100.5074
4	Fuel Outer Clad	Al	197.960	3.23757	76.4021	3.09945	73.1426
5	Water	H	21.6033	3.90710	384.0989	3.76845	370.4684
		O	171.623		0.1240		0.1196
6	Process Tube	Zr	499.200	4.39749	60.5774	4.25623	58.6315
7	Air	N	0.03813	4.56595	0.3042	4.42469	0.2759
		O	0.01168		0.0000		0.0000
8	Graphite	C	30881.4	5.67301	693.9298	5.52230	675.4942
		N	5.0984		50.5350		49.1924
		O	1.5623		0.0016		0.0016

TABLE X (Continued)

Target Cell							
#	Region	Isotope	Mass	SA ⁶³ _{1/v}	Abs. 1/v	SA ⁶³ _{sub-Cd}	Abs. sub-Cd
1	Target	⁶ Li	17.1235	0.55963	20131.1764	0.45666	17161.5027
		⁷ Li	26.6947		0.9826		0.8018
		Al	1524.1688		101.6817		82.9726
2	Target clad	Al	231.844	2.04403	56.4927	1.92893	53.3115
3	Water	H	12.7227	2.62000	151.6875	2.49966	144.7202
		O	100.973		0.0490		0.0467
4	Process tube	Zr	499.20	3.13736	43.2182	3.01179	41.4884
5	Air	N	0.03813	3.44477	0.2295	3.3192	0.2211
		O	0.01168		0.0000		0.0000
6	Graphite	C	30881.4	5.226052	639.2573	5.07203	620.4165
		N	5.0984		46.5535		45.1814
		O	1.5623		0.0015		0.0015
Total Supercell (Air Atmosphere)					60177.0133		54277.8976
Total Supercell (Vacuum)					59975.1264		54081.0623

$$f_{1/v} \text{ (Air Atmosphere)} = 0.5429, \quad f_{th} \text{ (Air Atmosphere)} = 0.5691$$

$$f_{1/v} \text{ (Vacuum)} = 0.5447, \quad f_{th} \text{ (Vacuum)} = 0.5711$$

$$t_{1/v} \text{ (Air Atmosphere)} = 0.3495, \quad t_{th} \text{ (Air Atmosphere)} = 0.3162$$

$$t_{1/v} \text{ (Vacuum)} = 0.3507, \quad t_{th} \text{ (Vacuum)} = 0.3173$$

Copper Poison Requirements in the Wet Supercell Lattice

M _O	M _{1/v}	SA ⁶³ _{1/v}	SA ^{Natural Cu} _{1/v}	Abs ^{Natural Cu} _{1/v}
95.70 gm.	98.3806 gm.	6.13637	5.118536	503.5646

$$k_{\infty} \text{ (Air Atmosphere)} = 1.0084 \pm .0017$$

$$k_{\infty} \text{ (Vacuum)} = 1.0118 \pm .0017$$

TABLE XI

Absorption Rates, $1/v$ and Thermal Utilizations (Dry Lattice)

<u>E-Type Cell</u>							
#	Region	Isotope	Mass	$SA_{1/v}^{63}$	Abs. $1/v$	SA_{sub-Cd}^{63}	Abs sub-Cd
1	Fuel	Al	1356.733	2.89952	468.9534	2.69149	435.3074
		^{235}U	44.7874		10491.2799		9738.5620
		^{234}U	1.0535		17.7045		16.3434
		^{238}U	5.6087		2.6454		2.4556
2	Fuel Clad	Al	229.62	3.58565	98.1492	3.38893	92.7643
3	Air	N	0.2286	3.77998	1.5098	3.58273	1.4301
		O	0.0701		0.0000		0.0000
4	Process tube	Zr	499.200	3.87034	53.3156	3.67257	50.5912
5	Air	N	0.03813		3.86906	0.2578	3.6
		O	0.01168		0.0000		0.0000
6	Graphite	C	30881.4	5.58317	682.9391	5.38309	658.4653
		N	5.0984		49.7359		47.9536
		O	1.5623		0.0016		0.0015

<u>U-Type Fuel</u>							
1	Air	N	0.04979	2.17984	0.1896	2.03193	0.1767
		O	0.01526		0.0000		0.0000
2	Fuel inner clad	Al	80.4626	2.12909	20.4220	1.97210	18.9162
3	Fuel	Al	170.847	2.34250	45.1872	2.17762	42.0066
		^{235}U	75.499		6739.8818		6265.4817
		^{238}U	7884.331		3005.3178		2793.7825
4	Fuel outer clad	Al	197.960	3.01203	71.0797	2.84461	67.1288
5	Air	N	0.1796	3.16037	0.9417	2.99242	0.9390
		O	0.0550		0.0000		0.0000
6	Process tube	Zr	499.200	3.26970	45.0415	3.10123	42.7207
7	Air	N	0.03813	3.42852	0.2284	3.26005	0.2172
		O	0.01168		0.0000		0.0000
8	Graphite	C	30881.4	4.86236	594.7696	4.67978	572.4360
		N	5.0984		43.3148		41.6883
		O	1.5623		0.0014		0.0013

TABLE XI (Continued)

				Target Cell			
#	Region	Isotope	Mass	SA ⁶³ _{1/v}	Abs. 1/v	SA ⁶³ _{sub-Cd}	Abs sub-Cd
1	Target	⁶ Li	17.1235	0.591637	22234.0428	0.46838	17601.9580
		⁷ Li	26.6947		1.0388		0.8224
		Al	1524.1688		107.4973		85.1021
2	Target clad	Al	231.844	2.12383	58.6983	1.98780	54.9387
3	Air	N	0.1057	2.32721	0.4298	2.18595	0.4037
		O	0.0324		0.0000		0.0000
4	Process tube	Zr	499.20	2.41963	33.3311	2.27575	31.3491
5	Air	N	0.03813	2.42322	0.1614	2.27934	0.1518
		O	0.01168		0.0000		0.0000
6	Graphite	C	30881.4	4.43767	542.8209	4.25741	520.7715
		N	5.0984		39.5316		37.9258
		O	1.5623		0.0013		0.0012
Total Supercell (Air Atmosphere)					57316.9632		50267.3409
Total Supercell (Vacuum)					57129.1089		50086.5800

$$f_{1/v} \text{ (Air Atmosphere)} = 0.5368, \quad f_{th} \text{ (Air Atmosphere)} = 0.5684$$

$$f_{1/v} \text{ (Vacuum)} = 0.5386, \quad f_{th} \text{ (Vacuum)} = 0.5705$$

$$t_{1/v} \text{ (Air Atmosphere)} = 0.3879, \quad t_{th} \text{ (Air Atmosphere)} = 0.3502$$

$$t_{1/v} \text{ (Vacuum)} = 0.3892, \quad t_{th} \text{ (Vacuum)} = 0.3514$$

Copper Poison Requirements in the Dry Supercell Lattice

M_o	$M_{1/v}$	SA ⁶³ _{1/v}	SA ^{Natural Cu} _{1/v}	Abs ^{Natural Cu} _{1/v}
51.01 gm.	53.5462 gm.	5.21638	4.351144	232.9872

$$k_{\infty} \text{ (Air Atmosphere)} = 1.0041 \pm .0017$$

$$k_{\infty} \text{ (Vacuum)} = 1.0074 \pm .0017$$

G. Determination of k_{∞} from These Experiments

The equations for calculating k_{∞} are derived from the four factor formula,

$$k_{\infty} = \eta \epsilon p f \quad (10)$$

It is assumed that the addition of copper to the boundary of the supercell will change only the thermal utilization. Since k'_{∞} of the supercell with the correct mass of copper on the supercell boundary (M_0) is unity,

$$k'_{\infty} = \eta \epsilon p f' = 1 \quad (11)$$

Thus, k_{∞} has been derived^(3,9) as the ratio of the unpoisoned to poisoned thermal utilizations of the supercell,

$$k_{\infty} = \frac{f}{f'}, \text{ where} \quad (12)$$

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 Eq. 9) is based on the assumption that the absorption rates in all the cell components, except for the resonance absorptions in ^{238}U , can be calculated by using the flux measured by a detector whose absorption cross section varies as $1/\sqrt{E}$ multiplied by the effective 2200 m/sec cross sections calculated by THERMOS. The material used as the absorber in the determination of $k_{\infty} 1/v$ must also have an effective cross section that varies as $1/\sqrt{E}$. The use of the four factor formula in the derivation of $k_{\infty} 1/v$ implies that:

$$k_{\infty} 1/v = \eta_{1/v} \epsilon p_{\text{non-}1/v} f_{1/v} \quad (13)$$

All non- $1/v$ epi-thermal absorption is accounted for in the resonance escape probability, $p_{\text{non-}1/v}$.

Eq. 12 can be rewritten in terms of absorption rates by use of Eq. 9,

$$k_{\infty}-1 = \frac{(\text{Abs})'_p}{\sum_i (\text{Abs})_i} + \frac{\sum_i [(\text{Abs})'_i - (\text{Abs})_i]}{\sum_i (\text{Abs})_i} \quad (14)$$

$(\text{Abs})'_p$ = relative $1/v$ absorption rate in the copper poison

$(\text{Abs})'_i$ = relative $1/v$ absorption rate in the i^{th} component of the poisoned supercell

$(\text{Abs})_i$ = relative $1/v$ absorption rate in the i^{th} component of the unpoisoned supercell.

A condition on Eq. 14 is that the absorption rates in the fuel for the poisoned and unpoisoned conditions are normalized to be equal. Since the correct mass of copper required to achieve a multiplication factor of unity in this supercell is very small (for both the wet lattice and the dry lattice), the copper addition would not measurably have changed the relative absorption rate, $(\text{Abs})_i$, in any of the cell components of the unpoisoned lattice. With this assumption, Eq. 14 reduces to the expression,

$$k_{\infty}-1 = \frac{(\text{Abs})'_p}{\sum_i (\text{Abs})_i} \quad (15)$$

Since the absorption rate in the copper poison is small with respect to the total supercell absorption rate, the measurement of k_{∞} in this experiment should be very precise.

H. Reactivity Change Due to Water Coolant Loss

Experimental values for the infinite medium neutron multiplication factor, k_{∞} , with the lattice coolant channels both wet and dry were used to obtain values for the reactivity effect due to water loss (see Table XII). The increase in the rate of neutron absorption in the lithium-aluminum target element due to the removal of the blocking effect of the coolant water

is larger than the rate of neutron absorption in the coolant water. The net effect is a decrease in reactivity when the water coolant is removed. Requirements on control strength for such a supercell are reduced since the maximum reactivity condition exists with coolant in the lattice.⁽¹⁰⁾

TABLE XII

Change in Reactivity Due to Water Coolant Loss

<u>Lattice Condition</u>	<u>k_{∞} (Air Atmosphere)</u>	<u>k_{∞} (Vacuum)</u>
Wet	$1.0084 \pm .0017$	$1.0118 \pm .0017$
Dry	$1.0041 \pm .0017$	$1.0074 \pm .0017$
$\frac{\Delta k \text{ (Wet} \rightarrow \text{Dry)}}{k_{\infty} \text{ (Wet)}}$	$-0.0043 \pm .0024$	$-0.0044 \pm .0024$

I. Coolant Loss Perturbation Measurements

Several perturbation measurements were made to determine the reactivity changes due to water coolant loss limited to a single cell in the test lattice. The reactivity worth was determined by measuring the relative masses, ΔM , of copper on the supercell boundary necessary to compensate for the change in reactivity. A dry coolant channel perturbation measurement was made in each type of cell in the matched spectrum of the wet lattice. Similarly, a wet perturbation measurement was made in each type of cell in the matched spectrum of the dry lattice. The reactivity worth of a mass of copper on the central supercell boundary was determined to be 11.5 and 12.4 gm Cu/mk in the matched spectrum of the wet and dry lattices, respectively (see Tables X and XI). Non-linear differences are readily apparent since the coolant affects several cells in the vicinity of the perturbation as well as the perturbed cell. Results of the perturbation measurements are listed in Table XIII. These results indicate that water loss in a single target cell will decrease reactivity but that water loss in a single fuel cell will increase reactivity.

TABLE XIIIResults of Coolant Perturbation MeasurementsMeasurements in the Matched Spectrum of the Wet Lattice:

<u>Central Supercell Coolant Condition</u>	<u>Mass of Copper to Compensate for Coolant Perturbation, ΔM</u>	<u>Change in Central Super- Cell Reactivity: Worth of Water, mk</u>
Dry (T), 2 wet (E), and Wet (U)	- 176 gm Cu	- 15.3
Dry (U), Wet (T), and 2 Wet (E)	+ 109 gm Cu	+ 9.5
Dry (E), Wet (T), Wet (U), and Wet (E)	+ 156 gm Cu	+ 13.5

Measurements in the Matched Spectrum of the Dry Lattice:

Wet (T), 2 Dry (E) and Dry (U)	+ 150 gm Cu	- 12.1
Wet (U), Dry (T), and 2 Dry (E)	- 82 gm Cu	+ 6.6
Wet (E), Dry (T), Dry (U), and Dry (E)	- 100 gm Cu	+ 8.1

V. MEASUREMENT OF NEUTRONIC PARAMETERS OF THE SUPERCELL LATTICE

The macroscopic lattice parameters (k_{∞} , p , ϵ , f , and C_0) cannot be measured directly, but they can be related to microscopic neutronic parameters which are measurable.

The measured microscopic neutronic parameters used to infer lattice parameters are the ratio of the epi-cadmium ^{238}U capture rate to the sub-cadmium ^{238}U capture rate, ρ^{28} ; the ratio of the ^{238}U fission rate to the ^{235}U fission rate, δ^{28} ; the ratio of the epi-cadmium ^{235}U fission rate to the sub-cadmium ^{235}U fission rate, δ^{25} ; the ratio of the epi-cadmium lithium-6 absorption rate to the sub-cadmium lithium-6 absorption rate, $\delta^{6\text{Li}}$; and the ratio of the total ^{238}U capture rate to the ^{235}U fission rate, C^* .

A. Experimental Determination of the Microscopic Neutronics Parameters

1. The Parameter ρ^{28}

The value of the ratio of epi-cadmium to sub-cadmium capture in ^{238}U , often called ρ^{28} , was measured in the 0.95% enriched uranium (U) cell of the central supercell. The values of ρ^{28} were obtained from bare ^{239}Np specific activities in the fuel relative to the sub-cadmium activity in the thermal column, and sub-cadmium copper relative activities. Since thermal neutron capture in ^{238}U has a slightly non- $1/v$ cross section energy dependence, THERMOS⁽⁷⁾ calculated non- $1/v$ factors for ^{238}U were used to infer the sub-cadmium ^{238}U capture relative activities from sub-cadmium copper relative activities from the equation:

$$\left(\frac{SA_{fuel}^{238}}{SA_{column}^{238}} \right)_{\text{sub-Cd}} = \left(\frac{SA_{fuel}^{Cu}}{SA_{column}^{Cu}} \right)_{\text{sub-Cd}} \left(\frac{g_{column}^{238}}{g_{fuel}^{238}} \right)_{\text{THERMOS}} \quad (16)$$

where,

$$g_i^{238} = \frac{\left(\frac{\sigma_c^{238}}{\sigma_{1/v}} \right)_i}{\left(\frac{\sigma_{1/v}}{\sigma_o^{238}} \right)_i} \quad (17)$$

and the cross section averages are taken from transport theory as thermal spectrum averages over the region i (i.e., fuel core region or PCTR thermal column region).

The epi-cadmium specific activity of ^{238}U capture in the fuel relative to the sub-cadmium specific activity in the thermal column was obtained from the measured bare specific activity of ^{238}U capture in the fuel relative to the sub-cadmium specific activity in the thermal column. This ratio was obtained from Eq. 16 by subtracting the relative sub-cadmium ^{238}U specific activity after corrections for thermal activation enhancement and depression were applied to the measured activities.

$$\frac{(SA_{fuel}^{238})_{\text{epi-Cd}}}{(SA_{column}^{238})_{\text{sub-Cd}}} = \frac{(SA_{fuel}^{238})_{\text{bare}}}{(SA_{column}^{238})_{\text{sub-Cd}}} - \left(\frac{SA_{fuel}^{238}}{SA_{column}^{238}} \right)_{\text{sub-Cd}} \quad (18)$$

The value of ρ^{28} was then determined from the ratio of epi-cadmium activities as measured in the fuel to the sub-cadmium activities as measured in the thermal column, Eq. 18, and the ratio of sub-cadmium activities from Eq. 16.

$$\rho^{28} = \frac{1}{\text{CdR}^{238} - 1} = \frac{\frac{(\text{SA}_{\text{fuel}}^{238})_{\text{epi-Cd}}}{(\text{SA}_{\text{column}}^{238})_{\text{sub-Cd}}}}{\left(\frac{\text{SA}_{\text{fuel}}^{238}}{\text{SA}_{\text{column}}^{238}} \right)_{\text{sub-Cd}}} = \frac{(\text{SA}_{\text{fuel}}^{238})_{\text{epi-Cd}}}{(\text{SA}_{\text{fuel}}^{238})_{\text{sub-Cd}}} \quad (19)$$

Differences in resonance shielding and neutron source depression caused by the insertion of cadmium in the fuel were eliminated by the substitution of copper activation data. Results of these measurements are listed in Table XIV.

TABLE XIV

Experimentally Determined Microscopic Neutronic Parameters

Cell Type		ρ^{28}	δ^{28}	δ^{25}	$\delta^{6\text{Li}}$	C*
(U)	Wet	0.693+.014	0.107+.008	0.0656+.0020		0.837+.025
	Dry	0.852+.017	0.103+.003	0.1029+.0031		1.009+.030
(E)	Wet			0.0692+.0021		
	Dry			0.0769+.0023		
(T)	Wet				0.226+.006	
	Dry				0.263+.007	
Central	Wet	0.693+.014	0.027+.002	0.0683+.0020	0.226+.006	0.212+.006
Supercell	Dry	0.852+.017	0.023+.002	0.0826+.0025	0.263+.007	0.218+.006

2. The Parameter δ^{28}

The measurement of the ^{238}U to ^{235}U fission ratio, commonly called δ^{28} , was obtained from the ratio of the measured fission product activity in a uranium foil (depleted to 15 ppm ^{235}U) to the measured fission product activity in a 0.95% enriched uranium fuel foil, $\gamma(t)$. These foils were irradiated simultaneously in the separable (U) fuel element. The function $F(t)$ is the ratio, at time t after irradiation, of counts originating from ^{238}U fission products to counts from ^{235}U fission products in uranium of the same composition as the fuel. Experimental values for $F(t)$ were obtained from the equation:

$$F(t) = \frac{\frac{N_F^{28}}{N_D^{28}} \gamma(t) - \frac{N_D^{25}}{N_D^{28}} \frac{N_F^{28}}{N_F^{25}}}{1 - \frac{N_N^{28}}{N_D^{28}} \gamma(t)} \quad (20)$$

where, N^{25} and N^{28} are the nuclei densities of ^{235}U and ^{238}U , respectively. The subscripts D and F refer to depleted uranium, and the uranium composition of the fuel core, respectively. The quantity $\gamma(t)$ is the ratio, at time t after irradiation, of the measured fission product activity in the depleted uranium foil to the activity of the uranium fuel foil. These activities were corrected for background, dead time, residual activity, and differences in foil weight.

In order to permit use of those simple counting techniques utilized in the measurement of $F(t)$ for determining δ^{28} , the function $P(t)$ is introduced such that,

$$\delta^{28} = P(t) F(t) . \quad (21)$$

The function $P(t)$ is defined as the count rate in the energy interval (510-675 keV) at time t per ^{235}U fission, divided by the count rate in the energy interval (510-675 keV) at time t per ^{238}U fission. This function was obtained from the measurement of the standard value of δ^{28} by the 1.6 MeV ^{140}La gamma ray activation technique developed by J. R. Wolberg, et al.,⁽¹⁷⁾ and from the usual measurement of $F(t)$ on the same two foils. It has been shown that the effect of the neutron energy spectrum on the function $P(t)$ is negligible for slightly enriched uranium in well moderated systems.⁽¹⁷⁾ This function was obtained from Ref. (18) and is shown in Figure 20. Results of these measurements are listed in Table XIV.

FIGURE 20 The Function $P(t)$

3. The Parameter δ^{25}

The parameter δ^{25} is a neutron spectral indicator for the fuel in the supercell lattice. The ratio δ^{25} is defined by the relation:

$$\delta^{25} = \left(\frac{\text{average epi-cadmium } ^{235}\text{U fission rate in the fuel}}{\text{average sub-cadmium } ^{235}\text{U fission rate in the fuel}} \right) \quad (22)$$

or,

$$\delta^{25} = \frac{1}{(\text{Cd ratio } ^{235}\text{U fission} - 1)} \quad (23)$$

Uranium-aluminum foils (93% ^{235}U) inserted in the separable fuel elements in the central supercell and in the thermal column were irradiated simultaneously. Separate irradiations of bare and cadmium covered foils inserted in the fuel elements were normalized to the bare foil in the thermal column for each irradiation. Fission product activity counting data was analyzed by computer code APDAC⁽⁶⁾ which corrects the data for activity decay during counting, room background, foil mass variation, and residual activity. The ratio δ^{25} was thus determined from the equation;

$$\delta^{25} = \frac{\frac{(SA_{\text{fuel}}^{235})_{\text{epi-Cd}}}{(SA_{\text{column}}^{235})_{\text{sub-Cd}}}}{\frac{(SA_{\text{fuel}}^{235})_{\text{sub-Cd}}}{(SA_{\text{column}}^{235})_{\text{sub-Cd}}}} = \frac{(SA_{\text{fuel}}^{235})_{\text{epi-Cd}}}{(SA_{\text{fuel}}^{235})_{\text{sub-Cd}}} \quad (24)$$

Results of these measurements are listed in Table XIV.

4. The Parameter $\delta^{6\text{Li}}$

The ratio $\delta^{6\text{Li}}$ is a neutron spectral indicator for the lithium target.

Its definition is analogous to that of δ^{25} :

$$\delta^{6\text{Li}} = \left(\frac{\text{average epi-cadmium } ^6\text{Li absorption rate in the target}}{\text{average sub-cadmium } ^6\text{Li absorption rate in the target}} \right) \quad (25)$$

or,

$$\delta^{6\text{Li}} = \left(\frac{1}{\text{Cd Ratio } ^6\text{Li Absorption} - 1} \right) \quad (26)$$

Copper foils inserted in the separable target element were used to infer the relative reaction rates in ^6Li . Since the ^6Li absorption cross section varies as $1/\sqrt{E}$, the measured epi-cadmium copper activation reaction rate in ^{63}Cu was corrected for the non- $1/v$ dependence of the cross section,

$$(\text{SA}_{1/v}^{63})_{\text{epi-Cd}} = (\text{SA}_{\text{meas.}}^{63})_{\text{epi-Cd}} \left(1 - \frac{\text{RI}_{\text{ex}}^{63}}{\text{RI}_{\text{epi-Cd}}^{63}} \right) \quad (27)$$

After corrections for flux perturbations due to the insertion of copper foils were applied to the activation measurements (see VI-D), the ratio $\delta^{6\text{Li}}$ was determined from the equation:

$$\delta^{6\text{Li}} = \frac{\frac{(\text{SA}_{1/v}^{63})_{\text{target}}}{(\text{SA}_{1/v}^{63})_{\text{sub-Cd}}} \left(\frac{\sigma_o^{6\text{Li}}}{\sigma_o^{63}} \right)}{\frac{(\text{SA}_{1/v}^{63})_{\text{target}}}{(\text{SA}_{1/v}^{63})_{\text{sub-Cd}}} \left(\frac{\sigma_o^{6\text{Li}}}{\sigma_o^{63}} \right)} = \frac{(\text{SA}_{1/v}^{63})_{\text{target}}}{(\text{SA}_{1/v}^{63})_{\text{sub-Cd}}} \quad (28)$$

Results of these measurements are listed in Table XIV.

5. The Parameter C*

The microscopic parameter C* is the quantity measured to determine the rate ^{239}Pu is formed in relation to the fission rate in ^{235}U . The ratio C* is defined by the relation:

$$C^* = \left(\frac{\text{average total } ^{238}\text{U capture rate in the fuel}}{\text{average total } ^{235}\text{U fission rate in the fuel}} \right) \quad (29)$$

Eq. 29 can be rewritten in terms of flux ϕ , cross section σ , and the nuclei density N:

$$C^* = \frac{N^{28} \int_0^\infty \sigma_c^{28}(E) \phi(E) dE}{N^{25} \int_0^\infty \sigma_f^{25}(E) \phi(E) dE} \quad (30)$$

The cross sections are considered to be averaged over the neutron spectrum in the fuel so that

$$N^{28} \int_0^\infty \sigma_c^{28}(E) \phi(E) dE = N^{28} \bar{\sigma}_c^{28} \phi \quad (31)$$

and,

$$N^{25} \int_0^\infty \sigma_f^{25}(E) \phi(E) dE = N^{25} \bar{\sigma}_f^{25} \phi \quad (32)$$

where,

$$\bar{\sigma}_i = \frac{\int_0^\infty \sigma_i(E) \phi(E) dE}{\int_0^\infty \phi(E) dE} \quad (33)$$

Substituting the above equations into Eq. (30) gives:

$$C^* = \left(\frac{N^{28}}{N^{25}} \right) \left(\frac{\bar{\sigma}_c^{28}}{\bar{\sigma}_f^{25}} \right) \quad (34)$$

The N^{28}/N^{25} atom ratio is known from mass spectrometer analysis. This leaves the cross section ratio, $\bar{\sigma}_c^{28} / \bar{\sigma}_f^{25}$, to be experimentally measured.

Identical sector foils were irradiated simultaneously both in the fuel and in the PCTR thermal column.

The fuel-to-thermal column ratios of fission rates and capture rates are written as follows:

$$\frac{\phi_f (\bar{\sigma}_f^{25})_f}{\phi_c (\bar{\sigma}_f^{25})_c} \quad (35)$$

$$\frac{\phi_f (\bar{\sigma}_c^{28})_f}{\phi_c (\bar{\sigma}_c^{28})_c} \quad (36)$$

where $()_f$ refers to fuel and $()_c$ refers to thermal column. Multiplying by the corresponding average thermal cross section in the thermal column,

$$\frac{\phi_f (\bar{\sigma}_f^{25})_f}{\phi_c (\bar{\sigma}_f^{25})_c} (\bar{\sigma}_f^{25})_c = \frac{\phi_f}{\phi_c} (\bar{\sigma}_f^{25})_f \quad (37)$$

$$\frac{\phi_f (\bar{\sigma}_c^{28})_f}{\phi_c (\bar{\sigma}_c^{28})_c} (\bar{\sigma}_c^{28})_c = \frac{\phi_f}{\phi_c} (\bar{\sigma}_c^{28})_f$$

Solving for $(\bar{\sigma}_c^{28})_f / (\bar{\sigma}_f^{25})_f$ yields:

$$\frac{(\bar{\sigma}_c^{28})_f}{(\bar{\sigma}_f^{25})_f} = \frac{\frac{\phi_f (\bar{\sigma}_c^{28})_f}{\phi_c (\bar{\sigma}_c^{28})_c}}{\frac{\phi_f (\bar{\sigma}_f^{25})_f}{\phi_c (\bar{\sigma}_f^{25})_c}} \left(\frac{(\bar{\sigma}_c^{28})_c}{(\bar{\sigma}_f^{25})_c} \right) \quad (39)$$

Let R stand for the fuel-to-thermal column activity ratio, so that:

$$\frac{(\bar{\sigma}_c^{28})_f}{(\bar{\sigma}_f^{25})_f} = \frac{R^{28}}{R^{25}} \frac{(\bar{\sigma}_c^{28})_c}{(\bar{\sigma}_f^{25})_c} \quad (40)$$

The values for $\bar{\sigma}_c^{28}$ thermal and $\bar{\sigma}_f^{25}$ thermal are obtained from program THERMOS⁽⁷⁾ as the sub-cadmium average cross sections over the thermal column neutron spectrum. The values for R^{28} and R^{25} are defined as follows:

$$R^{28} = \frac{(SA_f^{28})_{bare}}{(SA_c^{28})_{bare} - (SA_c^{28})_{epi-Cd}} \quad (41)$$

$$R^{25} = \frac{(SA_f^{25 \text{ F.P.}})_{bare}}{(SA_c^{25 \text{ F.P.}})_{bare} - (SA_c^{25 \text{ F.P.}})_{epi-Cd}} \quad (42)$$

where,

$(SA_f^{28})_{bare}$ = The total ^{238}U capture specific activity of fuel in the core (measured by the ^{239}Np peak activity)

$(SA_c^{28})_{bare}$ = The total ^{238}U capture specific activity of the fuel in the thermal column (measured by the ^{239}Np peak activity)

$(SA_f^{25 \text{ F.P.}})_{bare}$ = The total ^{235}U fission product specific activity of the fuel in the core

$(SA_c^{25 \text{ F.P.}})_{bare}$ = The total ^{235}U fission product specific activity of the fuel in the thermal column.

The epi-cadmium specific activity of ^{238}U capture in the thermal column is estimated to be 0.7% of the bare ^{238}U capture specific activity, from the measured 0.005" gold cadmium ratio of 218 ± 8 in the thermal column

rotator position. The epi-cadmium ^{235}U fission product specific activity in the thermal column is negligible. Results of the C* measurements are listed in Table XIV.

6. Experimental Arrangement for the Measurement of ρ^{28} , δ^{28} , δ^{25} , $\delta^{6\text{Li}}$, and C*

The microscopic parameters were measured by irradiating, simultaneously, sets of detector foils in separable elements in the central supercell and identical foils of each type in the PCTR external column. The special separable elements are shown in Figure 21, partially disassembled along with foil holders and other provisions for foil traverses in the central supercell. Bare and cadmium covered foil sets were activated in separate irradiations. The normalization between separate irradiations was obtained from specific activities measured in the central supercell, relative to bare foils of the same type irradiated, simultaneously, in the thermal column. Special sector shaped foils were fabricated to integrate the neutron reaction rate over the area of the fuel elements, in which they are inserted. Similarly, copper quadrant foils inserted in the separable target element give the proper reaction rate averages over the target core's cross sectional area.

The set of uranium foils inserted in the separable (U) element consisted of a 0.95% enriched uranium foil, a depleted uranium foil (15 ppm ^{235}U), and a 7 wt% uranium-aluminum (93% ^{235}U) foil. Each foil was 0.003" thick, and was sandwiched between two 0.001" thick aluminum fission product "catcher" foils to prevent fission products produced in uranium of a differing enrichment from reaching the detector foils. Cadmium covers in the separable fuel elements, both (E) and (U), were

FIGURE 21

Separable Elements and Provisions for Foil
Activation Measurements

designed so that they displaced the aluminum cladding, in order to allow the inside dimensions of the cover to be identical to the fuel core dimensions. Foil sets placed inside the cadmium cover were between two 0.045" wafers of the fuel core material, also inside the cadmium cover, to minimize the cadmium "window" effect for neutrons of resonance energies. A schematic drawing of the uranium foil arrangements in the separable (U) element is shown in Figure 22. Bare foils were placed in holders machined from the fuel core material. In order to obtain spatial detail of the reaction rate integrals, a copper sector foil in the fuel and a copper quadrant in the target were dissected into several annular regions after irradiation. These foil peices were counted separately and yielded a histogram of specific activities relative to the monitor foil in the external thermal column.

7. Counting Techniques for ^{239}Np and Fission Product Activities

The Physical Constants Test Reactor (PCTR) is a low power, bare, graphite moderated reactor in which one face of the reactor is moveable to allow access to the test core (see Figure 23). The neutron flux level in the test core is limited to $\sim 10^9$ neutrons/cm²sec. Maximum irradiation times are limited to approximately two hours due to increasing personnel radiation exposure between faces of the reactor after irradiation. The neutron activation of the ^{140}La gamma ray from fission products at the maximum power level for two hours in the PCTR is sufficiently low so that extremely long count times (from 200 to 300 minutes per count) are required. It is, thus, necessary to measure the fission product activity integral in a given energy interval in order to obtain reasonable statistical results with short count times (approximately two minutes per count).

The quantity $\gamma(t)$ is the ratio, at time t after irradiation, of the measured fission product activity in the uranium foil (depleted to 15 ppm ^{235}U) to the measured fission product activity in the 0.95% enriched uranium foil. The second foil matches the enrichment in the (U) fuel element in which the foils were irradiated. The gamma ray activities were counted between 510 kev and 675 kev in order to exclude the ^{239}Np pile-up peaks at lower energies. The upper energy limit was chosen due to counting procedure considerations. A 3" x 3" NaI (Tl) crystal γ -ray scintillation counter was used with a 512 channel multichannel analyzer to obtain the ^{239}Np activity in each uranium foil simultaneously with the fission product activity.

Bare Foil Irradiation

Cadmium Covered Foil Irradiation

FIGURE 22

Uranium Foil Arrangements in the Separable (U) Element for the Microscopic Parameter Measurements

FIGURE 23

The Physical Constants Testing Reactor (PCTR)

A narrow "window" between 90 kev and 120 kev was used to count the 106 kev ^{239}Np γ -ray activity. An unirradiated monitor foil which matched the residual activity of the foil used in the irradiation (before the irradiation was performed), was counted after the irradiated foil. The irradiated foil γ -ray spectrum was stored in the analyzer memory while the unirradiated monitor foil was being counted. The unirradiated foil γ -ray spectrum was then subtracted from the irradiated foil γ -ray spectrum to remove the activity due to background, natural decay, and residual activity in the irradiated foil. The resulting γ -ray spectrum, at decay time t after irradiation, was integrated between 90 kev and 120 kev and between 510 kev and 675 kev in the multichannel analyzer memory before being printed out.

To determine the magnitude of the contribution of fission products activity in the energy range of the ^{239}Np peak, the γ -ray spectral data of the 7 wt% uranium-aluminum (93% ^{235}U) foil was used. As previously shown,⁽¹⁶⁾ the small amount of ^{239}Np produced in the 93% enriched ^{235}U -Al foil can be neglected. The quantities F_E and F_U are the measured integral fission product activities between 510 and 675 kev for the 93% enriched ^{235}U -Al, and the 0.95% enriched uranium metal foil, respectively. What is to be determined is f_u , the fission product activity in the ^{239}Np counting interval. If the contribution from bremsstrahlung radiation and the scattering of higher energy gamma rays into the ^{239}Np counting interval is small, we can write:

$$\frac{f_u}{F_u} = \frac{f_E}{F_E} \quad , \quad (43)$$

which can be rewritten as:

$$f_u = \frac{f_E}{F_E} F_u \quad (44)$$

The unknown, f_u , is given in terms of directly measurable quantities. The ratio f_E/F_E is time dependent. Substitution of $r(t)$ for this ratio yields:

$$f_u = r(t)F_u \quad (45)$$

With the magnitude of f_u thus known, the ^{239}Np activity of a fuel foil at decay time, t , can be written as:

$$A^{\text{Np}}(t) = N'(t) - r(t)F_u(t) \quad (46)$$

where, $N'(t)$ is the gross measured activity in the ^{239}Np counting interval at time (t) minus the activity of background, natural decay, and residual activity. Similarly, the uranium foil (depleted to 15 ppm ^{235}U) also irradiated in the separable (U) element was analyzed to determine the ^{239}Np activity in the fuel. The results for the ^{239}Np activity relative to the thermal column from the fuel foils and the depleted uranium foils agree within less than $\pm 1\%$. This is considered to be an excellent check on the consistency of the method.

B. Determination of the Macroscopic Neutronic Lattice Parameters

1. The Fast Fission Effect

The fast fission factor, ϵ^{28} , is the term used to include the contribution of neutrons produced by fast fissions of ^{238}U in the calculation of the infinite medium neutron multiplication factor, k_∞ . The fast fission factor cannot be measured directly, but is related to a measured quantity, δ^{28} , by the equation:

$$\epsilon^{28} = 1 + \left(\frac{\nu^{28} - 1 - \alpha^{28}}{\nu^{25}} \right) \delta^{28} \quad (47)$$

where ν^{28} and ν^{25} are equal to the average number of neutrons emitted per fission of ^{238}U and ^{235}U , respectively, and,

$$\alpha^{28} = \frac{\int_{E_t}^{\infty} \phi(E) \sigma_c^{28}(E) dE}{\int_{E_t}^{\infty} \phi(E) \sigma_f^{28}(E) dE} \quad (48)$$

The fission neutron energy spectrum of ^{235}U was used for $\phi(E)$, where $\sigma_c^{28}(E)$ and $\sigma_f^{28}(E)$ are the energy dependent cross sections for radioactive capture and fission, respectively. The ^{238}U fission threshold energy, E_t , of 0.498 Mev was used in Eq. (48).

The quantities, ν^{28} and $\alpha_{\text{fast}}^{28}$, were calculated using computer code HRG.⁽¹⁹⁾ The quantity, ν^{25} , was calculated from the measured ^{235}U fission cadmium ratio in the fuel (CdR^{25}) and ν^{25} values from computer codes THERMOS⁽⁷⁾ and HRG⁽¹⁹⁾ by the equation,

$$\nu^{25} = \frac{\nu_{\text{THERMOS}}^{25} (\text{CdR}^{25} - 1) + \nu_{\text{HRG}}^{25}}{\text{CdR}^{25}} \quad (49)$$

The THERMOS calculation includes thermal neutron energies from 0 to 0.683 ev, and the HRG calculation includes all epi-thermal neutron energies from 0.683 ev to 10 Mev. Calculated values used to relate ϵ to δ^{28} are:

$$\begin{aligned} \nu^{25} &= 2.4317 \\ \nu^{28} &= 2.7373 \\ \alpha^{28} &= 0.3928 \end{aligned}$$

The substitution of these numerical values into Eq. (47) gives,

$$\epsilon^{28} = 1 + 0.5529 \delta^{28} \quad (50)$$

Eq. (50) is used to determine ϵ^{28} from the measured quantity, δ^{28} .

Values for ϵ^{28} inferred for both the wet and the dry supercell lattice are listed in Table XV.

TABLE XV

<u>Macroscopic Neutronic Lattice Parameters</u>					
<u>Cell Type</u>		<u>ϵ^{28}</u>	<u>$\Sigma_c^{238} / \Sigma_a^{235}$</u>	<u>$\Sigma_a^{6\text{Li}} / \Sigma_a^{235}$</u>	<u>p^{28}</u>
(U)	Wet	1.059 $\pm$.004	1.699 $\pm$.020		0.844 $\pm$.005
	Dry	1.057 $\pm$.004	0.828 $\pm$.023		0.792 $\pm$.008
(E)	Wet		0.015 $\pm$.001		
	Dry		0.014 $\pm$.001		
(T)	Wet				
	Dry				
Central	Wet	1.015 $\pm$.001	0.177 $\pm$.005	0.712 $\pm$.026	0.962 $\pm$.001
Supercell	Dry	1.013 $\pm$.001	0.182 $\pm$.005	0.785 $\pm$.029	0.955 $\pm$.001

2. The $^{238}\text{U}/^{235}\text{U}$ Absorption Ratio

The ratio of the total neutron capture rate in ^{238}U to the total neutron absorption rate in ^{235}U , $\Sigma_c^{238}/\Sigma_a^{235}$, is related to the rate of change of the fissile nuclei density in the fuel, since neutron capture in ^{238}U produces ^{239}Pu .

The total absorption rate $\Sigma_c^{238}/\Sigma_a^{235}$ can be determined from the measured microscopic parameters.

$$\frac{\Sigma_c^{238}}{\Sigma_a^{235}} = C^* \left(\frac{1}{1 + \alpha_{\text{total}}^{25}} \right) \quad (52)$$

$$\text{where } C^* = \frac{\bar{\sigma}_c^{28}}{\bar{\sigma}_f^{25}} \quad (\text{see V.A-5}) \quad (53)$$

$\alpha_{\text{total}}^{25}$ = spectrum averaged capture-to-fission ratio in ^{235}U

$$= \left[\frac{\alpha_{\text{sub-Cd}}^{25}}{\delta^{25}} + \alpha_{\text{epi-Cd}}^{25} \right] \left(\frac{\delta^{25} + 1}{\delta^{25}} \right) \quad (54)$$

The quantity C^* can also be expressed in terms of sub-cadmium cross sections, ρ^{28} , and δ^{25} in the fuel:

$$C^* = \left(\frac{1 + \rho^{28}}{1 + \delta^{25}} \right) \left(\frac{\Sigma_a^{238}}{\Sigma_f^{235}} \right)_{\text{sub-Cd}} \quad (55)$$

Hence, the sub-cadmium $^{238}\text{U}/^{235}\text{U}$ absorption ratio can be determined from the equation:

$$\left(\frac{\Sigma_a^{238}}{\Sigma_a^{235}} \right)_{\text{sub-Cd}} = C^* \left(\frac{1 + \delta^{25}}{1 + \rho^{28}} \right) \left(\frac{1}{\bar{\alpha}_{\text{sub-Cd}}^{25}} \right) \quad (56)$$

The quantities $(\bar{\alpha}^{25})_{\text{sub-Cd}}$ and $(\bar{\alpha}^{25})_{\text{epi-Cd}}$ were calculated by computer codes THERMOS⁽⁷⁾ and HRG,⁽¹⁹⁾ respectively. The values inferred for $\Sigma_c^{238}/\Sigma_a^{235}$ in the supercell lattice, both wet and dry, are listed in Table XV.

3. The $^6\text{Li}/^{235}\text{U}$ Absorption Ratio

The ratio of the total neutron absorption rate in ^6Li to the total neutron absorption rate in ^{235}U , $\Sigma_a^{6\text{Li}}/\Sigma_a^{235}$, was determined from foil activation data in the fuel and the target relative to the PCTR thermal column. Since the absorption cross section of ^6Li varies as $1/\sqrt{E}$, the $1/v$ copper-63 specific activity in the target was used to infer the ^6Li relative reaction rate.

$$\frac{\Sigma_a^{6\text{Li}}}{\Sigma_a^{235}} = \frac{\frac{(\text{SA}_{\text{target}}^{63})_{1/v}}{(\text{SA}_{\text{column}}^{63})_{\text{sub-Cd}}}}{\frac{(\text{SA}_{\text{fuel}}^{235})_{\text{total}}}{(\text{SA}_{\text{column}}^{235})_{\text{sub-Cd}}}} \left(\frac{N^{6\text{Li}}}{N^{235}} \right) \left(\frac{\bar{\sigma}_a^{6\text{Li}}}{\bar{\sigma}_f^{235}} \right) \text{thermal column} \left(\frac{1}{1 + \bar{\alpha}_{\text{total}}^{25}} \right) \quad (57)$$

Values inferred for $\Sigma_a^{6\text{Li}}/\Sigma_a^{235}$, in both the wet and dry supercell lattice, are listed in Table XV. The thermal neutron spectrum averaged cross sections for ^6Li and ^{235}U in the PCTR thermal column were calculated by THERMOS.⁽⁷⁾ The spectrum averaged capture-to-fission ratio

in ^{235}U was determined from Eq. (54), and the nuclei ratio of ^6Li to ^{235}U was determined by chemical and mass spectrographic analyses on the target core and fuel core materials.

4. The ^{238}U Resonance Escape Probability

A simple formula is obtained if all captures except ^{238}U resonance capture above the cadmium cutoff energy and neutron leakage are assumed negligible, then the resonance escape probability, p , can be expressed as follows:

$$p^{28} = \frac{\text{thermal absorptions}}{\text{total absorptions}} = \frac{\text{thermal abs.}}{\text{thermal abs.} + ^{238}\text{U resonance abs.}} \quad (58)$$

or,

$$p^{28} = \frac{(^{238}\text{U thermal abs.})(1/fG)}{(^{238}\text{U thermal abs.})(1/fG) + ^{238}\text{U epi-thermal abs.}} \quad (59)$$

Dividing through both numerator and denominator of Eq. (59) by $(^{238}\text{U thermal absorptions})(1/fG)$, one obtains:

$$p^{28} = \frac{1}{1 + \rho^{28} fG}, \quad (60)$$

where,

f = the thermal utilization

G = the ratio of the sub-cadmium ^{238}U capture to the sum of the sub-cadmium absorptions in the fuel

ρ^{28} = the ratio of the epi-cadmium ^{238}U capture rate to the sub-cadmium ^{238}U capture rate.

Values inferred for p^{28} in the supercell lattice, both wet and dry, are listed in Table XV. This simple relation, in spite of its severe

approximations, is quite useful for making comparisons of measurements made in similar systems.

VI. CORRECTIONS AND SYSTEMATIC ERRORS

A. Nitrogen Corrections

Nitrogen affects the null reactivity measurements of the supercell in two ways: first, air occupies the void spaces in the graphite and acts as a poison; second, upon removal of the central supercell ambient air enters and fills the cavity. Measured values of k_{∞} for the supercell in the PCTR are for such a lattice stacked in an air environment. To obtain the values for k_{∞} of these lattices stacked in a helium or vacuum environment, the $1/v$ utilization of nitrogen in the supercell (see Tables X and XI) should be removed, and included in the utilization in the poison required to achieve a multiplication of unity.

$$k_{\infty}(\text{vacuum}) = 1 + \frac{(\text{Abs})'_p + (\text{Abs})_{N_2}}{\sum_i (\text{Abs})_i - (\text{Abs})_{N_2}} \quad (61)$$

The increase in k_{∞} due to the removal of the air environment from the supercell lattice is ~ 3.4 mk.

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} , measurement using the expression:

$$\Delta\rho_N = DC \frac{P}{T} (M_N) (1-c) S_{Cu}^{\text{cavity}} \quad (62)$$

where, D = thermal disadvantage factor for the thickness of copper

(.010 in.) used in the determination of $S_{Cu}^{\text{cavity}} = 1.0110$;

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

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

$$P = \text{atmosphere pressure during reactivity measurement, mb};$$

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

$$M_{\text{N}} = \text{mass of nitrogen (at standard temperature and pressure) in the cavity} = 79.1577 \text{ grams.}$$

$$C = \frac{\sigma_{\text{O}}^{\text{N}}}{\sigma_{\text{O}}^{\text{Cu}}} \frac{A^{\text{Cu}}}{A^{\text{N}}} \frac{T_{\text{O}}}{P_{\text{O}}}$$

$$\sigma_{\text{O}}^{\text{N}} = 2200 \text{ m/sec microscopic absorption cross section of nitrogen} \\ = 1.88 \text{ b};$$

$$\sigma_{\text{O}}^{\text{Cu}} = 2200 \text{ m/sec microscopic absorption cross section of natural copper} = 3.79 \text{ b};$$

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

$$T_{\text{O}}, P_{\text{O}} = \text{standard temperature and pressure}$$

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

$$(1-c) = 1 - \left(\frac{m_1}{m_2} \right) \frac{RI_{\text{ex}}^{\text{Cu}}}{RI_{\text{epi-Cd}}^{\text{Cu}} (\text{CdR}-1)}, \quad (63)$$

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_{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-Cd 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} .

B. 1/v Mass Equivalent of a Mass of Copper

The requirement that the material used as the absorber in the determination of $k_{\infty 1/v}$ (see IV-G) 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 .

$$M_{1/v} SA_{1/v} m_2 = M_o (SA_{1/v} m_2 + SA_{res} m_1) \quad (64)$$

Account is taken of the worth of epi-thermal resonance absorptions in copper relative to the worth of 1/v absorptions. Using notation similar to that in the preceeding section, it has been shown⁽⁹⁾ that

$$M_{1/v} = M_o \left[1 + \left(\frac{m_1}{m_2} \right) \left(\frac{RI_{ex}^{Cu}}{CdR \cdot RI_{epi-Cd}^{Cu} - RI_{ex}} \right) \right] \quad (65)$$

Copper strips 0.003 in. thick were inserted at the boundary of the super-cell, and the cadmium ratio of the copper at the boundary was measured with 0.003 in. thick copper foils inserted in these strips. Effective resonance integrals for 0.003 in. thick natural copper were taken from measurements by Bennett.⁽¹¹⁾ Values for $M_{1/v}$ are only a few percent greater than M_0 , and are included in Tables X and XI.

C. Counter Efficiency Correction for Dissected Foils

The irradiated copper foils used to measure the relative reaction rates in the target material and the fuel material had a variable specific activity as a function of radial symmetry due to large disadvantage factors in the target and fuel materials. The distribution of the activity induced in a detector foil affects the overall efficiency of the scintillation counting system, since the counter efficiency varies with distance from the center of the crystal. Copper foils irradiated in the external thermal column of the PCTR had a constant specific activity as a function of radial symmetry. Thus, the counter efficiency function must be removed from the measured data in order to obtain relative reaction rates in the target and fuel materials.

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 as a function of its radial symmetry convoluted with the counter efficiency as a function of radial position.

$$\overline{SA}_{\text{observed}} = [SA(R)] * [\epsilon(r)] \quad (66)$$

Counter efficiency measurements with a ^{137}Cs pin point source were made by R. A. Bennett⁽¹¹⁾ 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 target and fuel, respectively, were dissected into small annular regions of approximately constant specific activity. By superposition of the dissected annular regions on the counter efficiency topographical plot, an effective counter efficiency for each region was obtained,

$$\epsilon_R = \frac{\int_R \epsilon(r) dA}{\int_R dA} \quad , \quad (67)$$

where,

$\epsilon(r)$ = counter efficiency at a distance r from the center of the surface of the crystal;

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

The dissected annular region was counted in the position that it would normally assume had the whole foil been placed on the crystal. The counter efficiency corrected specific activity for that region is given by:

$$SA_R(\text{corrected}) = \frac{SA_R(\text{observed})}{\epsilon_R} \quad (68)$$

Thus, the overall counter efficiency for a foil having regional specific activities obtained from Eq. (68) is determined by:

$$\bar{\epsilon} = \frac{\sum_{R=1}^n SA_R(\text{corrected}) A_R \epsilon_R}{\sum_{R=1}^n SA_R(\text{corrected}) A_R} \quad (69)$$

where, A_R = total area of the region R

n = number of annular regions in a whole foil.

D. Flux Enhancement and Depression Due to Insertion of Foils

The insertion of a detector foil in a medium to measure the relative reaction rate can introduce a significant perturbation in the flux in the vicinity of the foil.⁽¹²⁾ The magnitude of the perturbation is proportional to the difference between the macroscopic absorption cross sections for the medium and the foil. Corrections to the measured foil activities due to foil perturbation effects were calculated in order to infer relative reaction rates in the unperturbed regions of each medium. The derivation for the fraction of the measured foil activity, which is due to the flux perturbation in a flat foil of thickness t , and diameter L , is summarized as follows: if a foil of macroscopic absorption cross section Σ_{foil} is placed in a medium 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 $\ell_o \Sigma_{\text{foil}}$. The fractional flux peaking in the foil is $\ell_o (\Sigma_{\text{medium}} - \Sigma_{\text{foil}})$ if $\ell_o \Sigma_{\text{foil}}$ and $\ell_o \Sigma_{\text{medium}}$ 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,

$$\frac{A_{\text{foil}} - A_o}{A_{\text{foil}}} = \frac{\int \ell_o (\Sigma_{\text{medium}} - \Sigma_{\text{foil}}) \ell_o \Sigma_{\text{foil}} f(\ell_o) d\ell_o}{\int \ell_o \Sigma_{\text{foil}} f(\ell_o) d\ell_o} \quad (70)$$

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

$$\ell_o = \frac{t}{\sin \theta}, \text{ for } \theta > \frac{t}{L} \quad (71)$$

For an isotropic flux, neglecting edge effects,

$$f(\ell_o)d\ell_o = \sin \theta \cos \theta d\theta \quad (72)$$

Substitution for Eq's. (71) and (72) into Eq. (70) gives:

$$\frac{A_{\text{foil}} - A_o}{A_{\text{foil}}} = t(\sum_{\text{medium}} - \sum_{\text{foil}}) \ln(L/t). \quad (73)$$

Sub-cadmium activities of foils placed in the target, fuel, coolant, and moderator regions of the central supercell were corrected by the use of Eq. (73) in conjunction with thermal neutron spectrum, region averaged, foil, target, fuel, coolant, and moderator cross sections calculated by THERMOS⁽⁷⁾ (see Tables VIII and IX). Activities of foils irradiated in the PCTR external thermal column⁽⁵⁾ were corrected in a similar manner with cross sections averaged over an essentially thermal neutron energy spectrum in THERMOS.

Since the target absorption cross section varies as $1/\sqrt{E}$, the epi-cadmium activities of the copper foils placed in the target were corrected by the use of Eq. (73) in conjunction with epi-cadmium resonance integral data for a purely $1/v$ absorber and for natural copper.⁽¹¹⁾ Epi-cadmium activity corrections for the perturbation caused by the insertion of cadmium in the fuel were minimized by the use of fuel core slices inside the cadmium dish. The cadmium covered foils, thus, were inserted between

two slices of fuel core material inside the cadmium dish. This eliminates a window on either side of the foil which would allow streaming of neutrons at resonance energies. The cadmium also reduces the number of thermal fissions in the region near the foils, which decreases the number of fast neutrons being born near this region. Thus, the number of fast fissions in the cadmium covered foils are reduced. Both of these competing cadmium perturbation effects were evaluated to be of the order of 1% and the net effect is well within the 3% uncertainty in δ^{25} .

E. Central Cell End Effects

When the central supercell is removed from the test lattice in the course of performing null reactivity measurements, the front and rear end buffer cells each have one end of their process tubes exposed to the central supercell cavity. This exposure could affect the $\rho_{\text{cell-out}}$ reactivity measurement if neutron streaming from the cavity to these ends is appreciable. An attempt was made to measure these effects.

As shown by both experiment and 3-D WHIRLAWAY calculations,⁽¹³⁾ two errors are introduced in the measurement.⁽¹⁴⁾ One is the end effect that arises when the central supercell is removed, thus exposing the ends of the fuel and target rods to a much higher flux than these regions experience when the rods are continuous. Experiments with a 7 in. long and a 22 in. long central supercell were used to normalize the calculated results, and then the calculations were used to estimate an extrapolated correction for the measurements.

The second is an effect peculiar to the supercells. Since the zero gradient flux condition is not found at the geometric boundary of the supercell, removing the supercell causes a significant redistribution of

the flux in the graphite near the cell cavity. This redistribution has been observed experimentally with foil activation measurements and found to agree very well with the flux distribution calculations.⁽¹⁵⁾

The experiments with a 7.072 in. long and 21.875 in. long central supercell were used to normalize the calculated results by the expression:

$$\alpha = \frac{(k_{\infty}-1)_j^{\text{meas}} - (k_{\infty}-1)_p^{\text{meas}}}{\frac{(k_o^{\text{calc}} - k_E^{\text{calc}})_j}{(V_c)_j} - \frac{(k_o^{\text{calc}} - k_E^{\text{calc}})_p}{(V_c)_p}} \quad (74)$$

where superscripts j and p refer to the 7.027 in. long and 21.875 in. long central supercells, respectively.

k_o^{calc} = calculated multiplication factor outside the central test region;

k_E = calculated multiplication factor of lattice when the central supercell is removed

V_c = volume of central supercell

α = calculation normalization factor.

Then the calculations were used to estimate an extrapolated correction to find the true experimental value by correcting the 21.875 in. long supercell results by the equation:

$$(k_{\infty}-1)_{\text{redistribution effects}}^{\text{measured with end and boundary flux}} = \frac{(k_o^{\text{calc}} - k_E^{\text{calc}})}{V_c} \alpha + (k_{\infty}-1)_{\text{correct}} \quad (75)$$

The value of this correction for the particular case considered is ≈ 13 mk on the 21.875 in. long supercell.

VII. CONCLUSIONS

Neutronic characteristics of multi-component supercells can be accurately measured in the PCTR. The success of previous two-component supercell measurements (BNWL-622 and BNWL-792) and these three-component supercell measurements suggest that neutronic characteristics for a four-component supercell of the same type could be just as easily measured.

Comparison of these results with those obtained in the 2.1 wt% enriched uranium fueled supercell with the same Li-Al target^(1,2) shows that the zero gradient flux boundary contours are shifted closer to the fuel columns in the 2E:U:T supercell than in the 3U (2.1 wt% enriched):T supercell. Thus, the spectrum is "softer" and the target utilization is larger. The fast fission effect is considerably reduced because of the absence of ^{238}U in the E cells. Neutron loss due to capture in ^{238}U is also considerably reduced in the 2E:U:T supercell.

The reactivity effect of coolant loss is negative. However, the decrease in reactivity when water coolant is removed is lower in magnitude than for the 3U (2.1 wt% enriched):T supercell.

A large amount of experimental data has been obtained for graphite moderated, water cooled, supercell lattices. These neutronic parameters and spatial distributions of neutron reaction rates are of value for theory-experiment correlation.

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