PCTR MEASUREMENT OF k_{∞}
FOR URANIUM-BISMUTH SUPERCELL

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by

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February 1, 1968

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INTRODUCTION

A measurement has been made of the neutronic parameters for a low absorption target in a supercell consisting of a three-to-two fuel-to-target ratio with separate tubes of uranium fuel and bismuth metal target. Each tube is water cooled and surrounded by a graphite moderator on an 8.0" lattice pitch.

The bismuth target elements were relatively larger (3.750" O.D.) than the uranium fuel elements (1.508" O.D.) in order to irradiate as much of the target material as possible because of the significantly low bismuth cross section. Four inch square hole bars were removed from each target cell to contain a round aluminum process tube with the target elements. The graphite hole bars for the fuel cells contained 2.0" O.D. holes and zirconium process tubes.

The experiment was conducted in the Physical Constants Testing Reactor (PCTR) for a zero exposure case at room temperature. The reactivity effect of coolant loss was included in these measurements.

SUMMARY

The principal benefits from the experiment are to be derived from the measured relative flux patterns. These measurements indicate the flux in the bismuth target is 2.9 times higher than in the uranium (See Figure 10A).

In addition to the flux distribution, values of the multiplication factors have been derived as listed in Table I. The experimental data necessary to derive the multiplication factors were found to be very sensitive to the PCTR driver fuel loading. In this particular case, the test cell extended to the boundaries of the PCTR test cavity so that leakage effects were experienced in both cell-in and cell-out measurements. It is estimated that the

reactivity worths of the cell in terms of the mass of copper necessary to achieve unit multiplication (k_{∞}) would vary as much as ± 150 grams with differing driver fuel patterns or as much as 14.5 mk in the value of $k_{\infty}-1$ for the cell with coolant and 17.0 mk for the cell without coolant.

TABLE I

Lattice Parameters Derived from PCTR Measurements

0.95 wt% Enriched Uranium Fuel and Bismuth Target

(3 Fuel - 2 Targets per Supercell)

<u>Lattice Condition</u>	<u>Thermal Utilization</u>	<u>k_{∞} (Air Atm.)</u>	<u>k_{∞} (Vacuum Atm.)</u>	<u>M_o (Cu, gms)</u>
Wet Fuel - Wet Target	0.71187 ± 0.00597	0.87767 ± 0.01455	0.87681 ± 0.014	-1182.7 ± 154.2
Dry Fuel - Dry Target	0.76703 ± 0.00655	0.95282 ± 0.01740	0.95251 ± 0.017	- 569.4 ± 155.3
Dry Fuel - Air Target	0.78332 ± 0.00650	0.95726 ± 0.01700	----- -----	- 488.0 ± 150.0

DESCRIPTION OF EXPERIMENT

A. Test Lattice

The test lattice was made-up with graphite moderator blocks arranged on 8" centers and stacked in a 5x5 array of fuel and target cells so that all the fuel was contained in the first, third, and fifth horizontal rows and the target was in the second and third horizontal rows, the reasons for which are explained in this section.

Copper poison could be added symmetrically around the uranium cells, but not the target cells, by undercutting the graphite blocks between each lattice space. The undercutting was done so that two strips of copper, each approximately 2.5" wide, could be attached to the face of each lattice block containing fuel. Because all cases were sub-critical,

the only necessary copper additions were for calibration of the sensitivity of the cells to the copper which is the reactivity effect per unit mass of copper.

- Uranium Fuel
KVE Core Model
- Metallic Bismuth
3.66" O.D. Core
0.045" Thick Aluminum Clad

Front Buffer 7.710"

Center Cell 22.075"

Rear Buffer 7.710"

FIGURE 1
PCTR Test Lattice and Supercell

B. Supercell Construction

The array of test cells inserted into the PCTR test cavity for this experiment are depicted in Figure 1. The supercell consisted of five separate graphite squares, stacked vertically with the two target cells adjacent and separating the three fuel cells. This specific arrangement was designed to permit the possibility of reducing coolant supply to relatively low power target channels which may be supplied via a single horizontal header and to increase the available coolant flow to the fuel tubes. Buffer cells were stacked adjacent to the five center cells so that the total test array consisted of five supercells side-by-side.

This larger array of the center test cell extended from the bottom of the PCTR test cavity to the top so that the outermost fuel channels were very close to PCTR driver fuel. The reactivity worth of the test cells was very sensitive to driver locations and it was difficult to achieve a proper spectrum match from top to bottom. These problems are discussed in a later section; however, it should be noted that the experimental lattice as depicted in Figure 1 was turned upside down later on in the experiment in order to achieve better neutron spectrum conditions.

The thermal column graphite at the top of the test reactor provided more appropriate buffer conditions to the single fuel channel in the linear array so that there was a better spectrum balance between the two fuel cells adjacent to the target cells, although a perfect match was found to be difficult to define and may never have been obtained.

C. Fuel and Target Dimensions

The fuel was an I&E model, 0.945 wt% enriched uranium with aluminum cladding, and the target was metallic bismuth, also clad in aluminum.

The center test cell was 22.075" long and contained three target or fuel pieces per cell. The target material was designed to be the same length as the fuel. Details of the center fuel and target cells are listed in Tables II and III, respectively.

The 0.945 wt% enriched uranium fuel was chosen primarily because of its availability. The lattice was graphite blocks arranged on 8" centers with 2" diameter holes for fuel channels and 4" square openings for target channels. The fuel cells contained zirconium process tubes which were cut and capped to contain the coolant.

The bismuth target elements were designed and fabricated specifically for this experiment based on the primary criteria of getting as much target material into the reactor as possible because of the relatively low absorption cross section of the bismuth. A detailed description of the bismuth target elements manufacturing process has been documented by W. E. Gurwell et al, and is available on request.

TABLE II

Geometry of Center Fuel Cell Containing Water Coolant

Region	Isotope	O.D.(cm)	Density gm/cm ³	Mass (gm)	Volume cm ³
Water		1.0973	1.0000		53.07
	H			5.9387	
	O			47.1752	
Fuel Clad	Al	1.3843	2.699	84.452	31.29
Fuel		3.6043	16.323 ^(a,b)	7959.830	487.642
	²³⁵ U			75.499	
	²³⁸ U			7884.331	
	Al		1.157 ^(c)	564.186	
Fuel Clad	Al	3.8329	2.699	199.742	74.006
Water		4.3739	1.000		196.471
	H			21.985	
	O			174.643	
Process	Zr	4.5740	6.40	504.752	78.867
Tube					
Void		5.0800	1.293x10 ⁻³		215.108
	N			0.245	
	O			0.034	
Graphite		22.9286 ^(d)	1.6714		22015.001
	C			36795.873	
	N			5.666	
	O			0.899	

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

(b) Density of 0.947 wt% enriched fuel 18.824 gm/cm³.

(c) Reduced density to account for fuel.

(d) Cylindricized diameter.

TABLE IIIGeometry of Center Target Cell Containing Water Coolant

Region	Isotope	O.D. (cm)	Density <u>gm/cm³</u>	Mass (gm)	Volume (cm ³)
Target	Bismuth	9.296	8.943 ^(a,b)	34035.825	3805.840
	Al		.2225 ^(c)	846.865	
Target clad	Aluminum	9.525	2.699	511.452	189.482
Water		9.728	1.000		172.288
	H			19.279	
	O			153.009	
Process tube	Aluminum	10.160	2.699	1020.676	378.182
Air		11.464	1.293x10 ⁻³		1241.796
	N			1.233	
	O			0.196	
Moderator		22.929 ^(d)	1.6714		17363.837
	C			29021.92	
	N			4.469	
	O			0.709	

-
- (a) Reduced density to account for target element caps.
 (b) Density of bismuth 9.75 gm/cc.
 (c) Reduced density to account for target.
 (d) Cylindricized diameter.

D. Isotopic Analysis Data

It is standard practice to obtain an isotopic analysis of the fuel and target material in a test lattice so that exact absorption rates may be derived from the data. The results of these analyses are listed in Table IV.

TABLE IV

Isotopic Analysis of Fuel and Target

Fuel Sample

<u>Isotope</u>	<u>at%</u>	<u>wt%</u>
^{238}U	98.996 ± 0.005	99.090 ± 0.005
^{236}U	0.0359 ± 0.0005	0.0356 ± 0.0005
^{235}U	0.961 ± 0.005	0.949 ± 0.005
^{234}U	0.0074 ± 0.0002	0.0074 ± 0.0002

Target Sample

Bismuth	99.995	99.995
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EXPERIMENTAL TECHNIQUES AND RESULTS

A. 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 Testing Reactor (PCTR) have been documented.^(2,3) A summary of the method for measuring k_{∞} used for this experiment is included here to make the data which follows more meaningful. Basically, the PCTR experiment follows three distinct procedures:

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

2. Neutron absorber measurements to determine the amount of neutron absorber (copper) required to achieve unit multiplication in the test cell.
3. The relative reaction rates of the components of the test cell are measured in both the lattice reduced to unit multiplication and the lattice without neutron absorber added to the test cell.

B. Spectrum Matching

The neutron energy distribution is usually inferred by measuring cadmium ratios and comparing the cadmium ratio in the center test cell with the values indicated by the buffer cells taken at equivalent positions. For this experiment the cadmium ratio data did not adequately define neutron spectrum match conditions but rather the epi-cadmium activity was a more appropriate criteria. In other words, due to the large size of the center cell, proper cadmium ratios could be achieved; however, the flux density would be unequal because of leakage effects at the edge of the supercell. Flux modifiers were added near the edge of the cell until not only the cadmium ratios were matched, but also the relative epi-cadmium activities between the cells were equivalent. Specifically, the criteria is as follows:

1. Cells 8 and 23 are the two uranium cells adjacent to the bismuth target cells. Therefore, in an infinite array of supercells, these two cells are expected to have an equivalent spectrum and flux density.

2. Likewise, the bismuth target cells would have an equilibrium spectrum because each one is bordered by one target cell and one fuel cell.
3. Therefore, the cadmium ratios must not only match but the specific activities of foils in equivalent positions must be equal or close to equal before a flux condition of an infinite array of such cells was assumed to exist in the PCTR.

Several attempts were made to obtain an equilibrium spectrum across the test lattice and the results are listed in Table V for the experiment with coolant and Table VI for the experiment without coolant. The mass of neutron absorber necessary to achieve unit multiplication was found to be very sensitive to the top and bottom end effects of the supercell; therefore, the measured masses of copper are listed with the foil data. Gold foils were irradiated to derive this data because of the useful decay time of the irradiated foils and primarily because of the narrow resonance absorption region when covered with cadmium.

The 1/2" diameter, .005" thick gold foils were placed in the longitudinal center of each cell on a horizontal radius four inches apart. Both bare foils and foils covered with .040" cadmium covers were used.

TABLE V

Relative Total and Epicadmium Activities of Gold Foils in Supercell
(Experiment with Coolant)

Cell #	PCTR Loading Number					
	6719A	6719B	6719C	6719D	6719E	6719F
3 (total)	0.9614	0.9506	0.9634	0.9583	0.9501	0.9563
(epi-Cd)	0.2148	0.2363	0.2383	0.2326	0.2270	0.2337
8 "	1.000	1.000	1.000	1.000	1.000	1.000
	0.1564	0.1631	0.1633	0.1590	0.1460	0.1440
13 "	1.1817	1.1116	1.0973	1.1015	1.1455	1.1191
	0.1253	0.1058	0.0995	0.0969	0.1034	0.1000
18 "	1.1408	1.0219	1.0213	1.0828	1.1384	1.1022
	0.1174	0.0959	0.0928	0.0972	0.1067	0.1021
23 "	0.8512	0.7396	0.7616	0.7668	0.9100	0.8717
	0.1783	0.1352	0.1403	0.1273	0.1588	0.1447

Grams of Copper Necessary to Achieve Unit Mult.

M_o (gm.Cu)	-1479	-532	-535	-499	-1034	-1002
---------------	-------	------	------	------	-------	-------

Errors on bare foil activities $\pm 0.25\%$

Errors on cadmium covered foil activities $\pm 0.50\%$

TABLE VI

Relative Total and Epi-cadmium Activities of Gold Foils in Supercell
(Experiment without Coolant)

Cell #	PCTR Loading Number						
	6718A	6718B	6718C	6718D	6718E	6718F	6718G
8 (total)	0.8341	0.8058	0.8282	0.8735	0.8565	0.7473	0.8074
(epi-Cd)	0.1603	0.1515	0.1594	0.1705	0.1652	0.1440	0.1559
13 "	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	0.1146	0.1155	0.1124	0.1161	0.1134	0.1203	0.1192
18 "	0.9370	0.9712	0.9514	0.9239	0.9164	0.9815	0.9629
	0.1054	0.1135	0.1081	0.1037	0.1008	0.1252	0.1192
23 "	0.0675	0.7024	0.6701	0.6340	0.6307	0.7070	0.6794
	0.1309	0.1451	0.1331	0.1182	0.1174	0.1709	0.1491

Grams Copper Necessary to Achieve Unit Multiplication

M _o (gm.Cu)	+30	-285	-42	+504	-939	-748	-407
------------------------	-----	------	-----	------	------	------	------

Errors on bare foil activities $\pm 0.25\%$

Errors on cadmium covered foil activities $\pm 0.50\%$

As illustrated in the data of the relative activities of the gold foils, no particular loading seemed to indicate an equilibrium spectrum had been adequately achieved; however, by putting this data into a three dimensional plot a reasonably significant result can be extrapolated. Figures 2 and 3 are pretty much self-explaining and illustrate the method used to derive the mass of copper necessary to achieve unit multiplication in the cases with and without coolant, respectively. There may be a better and more accurate method than the one illustrated. It seems reasonable that the relative activities between the cells and the measured absorber masses have a more direct relationship; however, none are immediately apparent at the time of this report writing.

FIGURE 2
Three Dimensional Plot of Gold Foil Activities vs Mass of
Copper for Cells With Coolant

FIGURE 3
Three Dimensional Plot of Gold Foil Activities vs Mass of
Copper for Cells Without Coolant

C. Reactivity Measurements

The mass of neutron absorber required to achieve unit multiplication in the test cell is determined by a series of reactivity measurements called the 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 in the reactor as an empty cavity. The center cell in this case was 22.075" long so that the cavity consisted of five such cells removed in a vertical array. The cavity with front buffers removed is depicted in Figure 4 and illustrates the serious streaming effects which must have occurred during reactivity measurements with the center cell removed.

A reactivity series was done for each reactor loading and gold cadmium ratios were measured. A reactivity series consisted of measuring the reactivity of the lattice in four configurations:

- Reactivity with cell in;
- Reactivity with cell out;
- Reactivity with cell out and a specific amount of copper in the cavity;
- Reactivity with cell in and a specific amount of copper on the cell boundary.

Slots are provided in the lattice between each cell for insertion of copper poison strips at the cell boundaries. From these measurements the reactivity worths of three quantities are obtained:

1. The reactivity worth of the central supercell;
2. The worth of a small increment of copper on the cell boundary;

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

FIGURE 4
Picture of PCTR Test Cavity - Cell-Out Case Bismuth
Overbore Test

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

$$\Delta \rho_{\text{Cu}}^{\text{cavity}} = \rho_{\text{cell out}} - \rho_{\text{cell out with Cu in cavity}}.$$

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.

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

$$M_O = \frac{\Delta \rho_{\text{cell}} - \Delta \rho_{\text{N}_2}^{\text{boundary}}}{\Delta \rho_{\text{Cu}}^{\text{boundary}}} M_{\text{Cu}}^{\text{boundary}}$$

where, $M_{\text{Cu}}^{\text{boundary}} / \Delta \rho_{\text{Cu}}^{\text{boundary}}$ = the mass (grams) of copper per unit of reactivity measured with the cell in ($\rho_{\text{cell in}}$);

$\Delta \rho_{\text{N}_2}$ = the reactivity worth of the nitrogen in air which is present in the cavity vacated by the central supercell (see Section V-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 the function of the neutron energy distribution in the supercell. Due to the fact that the top and bottom ends of the supercell extended completely to the edge of the PCTR driver region, the measured mass of copper would change very significantly (± 500 grams) when driver positions were altered near the top and bottom of the supercell. This condition made it almost impractical to achieve an exact spectrum match; therefore, the correct mass of copper required to achieve unit multiplication had to be interpolated as a

function of the average bare and cadmium covered gold foil activities in the supercell. The diagram of these estimates were previously shown in Figures 2 and 3.

D. Relative Reaction Rate Measurements

Relative reaction rates of the test cell components are determined from copper foil activation measurements. The energy dependance 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 irradiating monitor foils in an external thermal column concurrently with the other foils. Figure 5 shown the fuel and target cells with the foil holders and separable elements used to obtain the relative activation rates of the copper foils.

The copper foil irradiations are done when the best spectrum match has been attained as indicated by comparisons of the data from the gold foil irradiations. Copper foils and pins were used throughout the lattice for the traverses in the graphite moderator, fuel, target, and the coolant channels. Foil locations in the moderator of the center cells are shown in Figures 6 and 7, illustrating the foil locations in the fuel and target elements of the center cell. The specific activities of the copper foils in the cell, relative to the foil in the external thermal column, are presented in two sections of Table VII for the supercell with coolant and without coolant, respectively. The activities were calculated using a revised version of the computer code APDAC-I⁽⁶⁾ which consists of counting data for activity decay during the counting period, room background, foil mass variations, and residual activity.

FIGURE 5
Fuel + Target Center Cells with Foil Holders and Separable
Elements for Obtaining Cu_{63} Activities

FIGURE 6
Foil Locations for Measuring Copper Activities in Moderator

FIGURE 7
Typical Foil and Pin Holders for Fuel and Target Cells
(Not Drawn to Scale)

FIGURE 8
Axial Traverse Cu_{63} Activity with Coolant

FIGURE 9
Axial Traverse Cu_{63} Activity Without Coolant

Figures 8 and 9 are graphs of the relative copper-63 activity variation along the angular traverse direction for the supercell with and without coolant, respectively.

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

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

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

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

The axial distribution of $1/v$ copper-63 reaction rates in the lattice with coolant is shown in Figures 10 and 11 for the various test cell conditions.

The uranium foil holders in the fuel were designed to contain quadrant foils which were made to integrate the neutron reaction rate over the area of the fuel. The same integrations were done over the target area by measuring the activity of bare and cadmium covered copper pins strategically located in special holders constructed of bismuth target material.

In order to obtain spatial detail of the reaction rate ingetrals, the sector foils in the fuel were dissected into several annular regions after irradiation. These foil pieces were counted separately and the

FIGURE 10A
Cylindricized - Radial Traverse Between Fuel and Target Cells
with Coolant
Relative Reaction Rates in Copper 63 (SA)

FIGURE 10B
Cylindricized - Radial Traverse Between Fuel Cells in the
Lattice with Coolant - Relative Reaction Rates in Copper 63
(SA)

FIGURE 11A
 Cylindricized - Radial Traverse Between Fuel and Target Cells
 in the Lattice Without Coolant
 $\text{SA}(r)$ = Relative Cu_{63} Reaction Rate

FIGURE 11B
 Cylindricized - Radial Traverse Between Fuel Cells Without
 Coolant
 $SA(r)$ = Relative Copper 63 Reaction Rate

results were plotted to indicate the flux pattern through the fuel.

The pins provided the same type of histogram for the bismuth target.

Fission foils - depleted U, ^{235}U aluminum and 0.80% enriched uranium foils, were irradiated in the separable elements with the copper. The fission foils were separated by having one mil aluminum fission product catcher foils on their surfaces. All types of foils were irradiated, both bare and with cadmium covers in separate irradiations.

E. Neutron Cross Sections

Thermal neutron spectrum averaged microscopic cross section values, calculated by transport theory, were obtained from the computer code THERMOS.⁽⁷⁾ Single cell calculations were made for each type of cell both with and without coolant. The geometry was cylindricized and reflecting boundary conditions were set at the outer boundary. The location of the outer boundaries of the cells determined from the equivalent cell radius which was derived experimentally from sub-cadmium zero net current boundaries. Topographical plots of the sub-cadmium copper-63 relative absorption which indicate the zero net current boundaries are plotted in Figures 10 (A and B) for the lattice without coolant. These figures indicate that the flux peak, normally between fuel and target cells, is actually in the bismuth target. Due to the low cross section of the bismuth, the target cells seem to have very little absorption effect on the neutrons which migrate from the fuel cells. Since no specific boundary exists, the volume of moderator (graphite) in each target cell was added to the adjacent fuel cell in order to derive a boundary for the THERMOS calculations.

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 it is necessary to assume both the energy distribution of the neutrons and the characteristic spectral indices; e.g., a Maxwellian with an estimated neutron temperature. In general, the cross sections calculated by THERMOS are defined as:

$$\hat{\sigma}(r) = \frac{\int_0^E \sigma(E) \phi(E,r) dE}{\int_0^E \sqrt{E_0/E} \phi(E,r) dE} \quad (1)$$

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

$$E_0 = 0.0253 \text{ ev}$$

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

Region averaged THERMOS cross sections calculated by the technique described above are presented in Table VIII for these lattices with coolant. One may note that as defined in equation (1), the values will be 2200 M/sec values unless the cross section is non- $1/v$ dependent for $0 \leq E \leq 0.683$ ev.

TABLE VII

Relative CU-63 Activity

Lattice Without Coolant		Lattice With Coolant			
Position No.	Radius Inches	Activity		Activity	
		Bare	Cd Covered	Bare	Cd Covered
1	1.595	4.3528	.430	6.7899	.427
2	2.095	4.6074		7.1318	
3	2.595	4.7572	.444	7.3855	.414
4	3.095	4.8519		7.5646	
5	3.595	4.8841	.454	7.6970	.402
6	4.095	4.8962		7.8047	
7	1.595	4.5868	.392	5.7460	.490
8	2.095	4.9782		5.8525	
9	2.595	5.2563	.388	5.8243	.517
10	3.095	5.4739		5.7322	
11	3.595	5.6178	.375	5.5457	.540
12	4.095	5.6207		5.3323	
13	4.095	5.7587		9.0747	
14	3.595	5.8859	.357	8.9207	.244
15	3.095	5.6324		8.7285	
16	2.595	5.4176	.338	8.4810	.256
17	2.095	5.3705		8.1915	
18	1.595	5.1866	.314	7.7653	.269
19	1.595	5.1105	.300	7.6140	.282
20	2.095	5.4414		8.0213	
21	2.595	5.6450	.316	8.2806	.281
22	3.095	5.7942		8.4858	
23	3.595	5.8819	.328	8.6503	.273
24	4.095	5.9058		8.7279	
25	1.595	5.2062	.274	7.3955	.316
26	2.095	5.6535		7.7553	
27	2.595	5.9577	.269	7.9725	.330
28	3.095	6.1578		8.1336	
29	3.595	6.2992	.265	8.2448	.342
30	4.095	6.5436		8.2659	
31	1.595	5.2633	.262	7.3006	.330
32	2.095	5.7741		7.6669	
33	2.595	6.1036	.250	7.8836	.350
34	3.095	6.3994		8.0215	
35	3.595	6.6415	.237	8.1385	.419
36	4.095	6.8036		8.1497	
37	3.85	7.0392	.218	9.7049	.160
38	3.35	7.0983		9.6979	
39	2.85	7.1388	.202	9.6396	.162
40	2.85	7.3433	.190	9.6316	.165
41	3.35	7.3284		9.6008	
42	3.85	7.3265	.197	9.7173	.164
43	2.85	6.9569		9.4944	.190
44	3.35	6.9962		9.5245	
45	3.85	6.9932	.159	9.5165	.197
46	2.85	6.9036	.160	9.3419	.206
47	3.35	6.6870		9.2988	
48	3.85	6.9573	.152	9.2107	
Ref.	Th-Column	1.000	1.000	1.000	1.000

TABLE VIII

Thermal Average Cross Sections
(from THERMOS)

Cell 3, Fuel with Coolant

Isotope	Region	$\bar{\sigma}_a$	$\bar{\sigma}_{a_{1/v}}^*$	$\hat{\sigma}_i = \frac{\bar{\sigma}_{a_i}}{(\bar{\sigma}_{a_{1/v}})_i}$
Hydrogen	1	0.23801	0.72563	0.32800
Oxygen	1	1.524x10 ⁻⁴		0.000210
Aluminum	2	0.15912	0.69180	0.23000
U-235	3	449.466	0.68608	655.14095
U-238	3	1.8968		2.76477
Aluminum	4	0.16618	0.72267	0.22995
Hydrogen	5	0.24946	0.76053	0.32800
Oxygen	5	1.5970x10 ⁻⁴		0.00021
Zirconium	6	0.13961	0.77561	0.18000
Nitrogen	7	1.35736		1.75005
Oxygen	7	1.6290x10 ⁻⁴		0.00021
Carbon	8	2.639x10 ⁻³	0.77619	0.00340
Nitrogen	8	1.3584		1.75005
Oxygen	8	1.630x10 ⁻⁴		0.00021
Copper	8	2.99334		3.79000

Cell 8, Fuel with Coolant (and Cell 23)

Hydrogen	1	0.24951	0.76071	0.32800
Oxygen	1	1.59730x10 ⁻⁴		0.000210
Aluminum	2	0.16502	0.71746	0.23000
U-235	3	468.904	0.71695	654.0261
U-238	3	1.97885		2.76009
Aluminum	4	0.17370	0.75520	0.23000
Hydrogen	5	0.23994	0.79249	0.32800
Oxygen	5	1.6641x10 ⁻⁴		0.00021
Zirconium	6	0.14571	0.80950	0.18000
Nitrogen	7	1.41665	0.80950	1.75003
Oxygen	7	1.70x10 ⁻⁴		0.00021
Carbon	8	2.76x10 ⁻³	0.81168	0.00340
Nitrogen	8	1.42048		1.75005
Oxygen	8	1.7404x10 ⁻⁴		0.00021
Copper	8	3.07628		3.79000

Cell 13, Target with Coolant (and Cell 18)

Bismuth	1			0.0340
Aluminum	2	0.18669	0.81168	0.23000
Hydrogen	3	0.26623		0.32800
Oxygen	3	1.70440x10 ⁻⁴		0.00021
Aluminum	4	0.18669		0.23000
Nitrogen	5	1.42028		1.75004
Oxygen	5	1.70440		0.00021
Carbon	6	2.75972x10 ⁻³		0.00340
Nitrogen	6	1.42048		0.23000
Oxygen	6	1.70440		0.00021

* $\sigma_{a_0} = 1.000$

F. Determination of 1/v Utilization

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.

$$f_{1/v} = \frac{(\bar{\Sigma}_a \phi V)_{\text{fuel}}}{(\bar{\Sigma}_a \phi V)_{\text{fuel}} + (\bar{\Sigma}_a \phi V)_{\text{cell}}} \quad (2)$$

The experimental values of the 1/v utilization are determined from measured distribution of the 1/v neutron reaction rate in copper-63. At space point r the 1/v absorption rate in copper-63 is:

$$\overline{SA}^{63}(r) = c \frac{N_o}{A^{63}} \hat{\sigma}(r)^{63} \int_0^{\infty} \sqrt{E_o/E} \phi(E, r) dE \quad (3)$$

where c is a space independent normalizing constant. A sample value of $\overline{SA}_\chi$ for the material, χ , in any given region may be obtained from the ratio:

$$\overline{SA}^\chi(r) = \frac{\hat{\sigma}^\chi(r) A^{63}}{\hat{\sigma}^{63}(r) A^\chi} \overline{SA}^{63}(r) \quad (4)$$

where A is the atomic weight.

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

$$(\text{Abs})^\chi = \frac{M^\chi \int_{\text{all of region } \chi} \overline{SA}^\chi(r) dV}{\int_{\text{all of region } \chi} dV} \quad (5)$$

where M^χ is the mass of material χ in the region. Finally, then, the 1/v utilization of material χ is:

$$f_{1/v}^\chi = \frac{(\text{Abs})^\chi}{\sum_i (\text{Abs})_i} \quad (6)$$

The absorption rates for all the components of the supercell and 1/v utilizations of these components are presented in Table IX.

TABLE IX

Experimental 1/v Absorption Rates and Utilizations
(Lattice With Coolant)

No.	Region	Isotope	(Abs)1/v	Cell 1/v Utilization	Unpoisoned Supercell 1/v Utilization
<u>Cell 3 (Fuel)</u>					
1	Water	H	101.9921	.006376	.001654
		O	0.0329	.000002	.000000
2	Fuel inner clad	Al	87.9727	.005519	.0014269
3	Fuel	²³⁵ U	9606.5361	.602741	.155818
		²³⁸ U	4178.0029	.262128	.067767
4	Fuel outer clad	Al	255.2408	.016014	.004140
5	Water	H	479.3254	.030073	.007775
		O	0.1547	.000010	.000003
6	Process tube	Zr	73.6970	.004624	.001195
7	Air	N	2.3541	.000148	.000038
		O	0.0000	.000000	.000000
8	Graphite	C	1079.3465	.067720	.017507
		N	72.9307	.004576	.0011829
		O	0.0012	.000000	.0000000
TOTAL: 15937.5870					.258508
<u>Cell 8 and 23 (Fuel)</u>					
1	Water	H	107.3671	.006132	.0017415
		O	0.0347	.000002	.000563
2	Fuel inner clad	Al	96.5831	.005516	.001567
3	Fuel	²³⁵ U	10483.9293	.598737	.170049
		²³⁸ U	4562.0127	.260537	.073996
4	Fuel outer clad	Al	328.0526	.018735	.005321
5	Water	H	566.8979	.032376	.009195
		O	0.1829	.000010	.000003
6	Process tube	Zr	85.8889	.004905	.0013931
7	Air	N	2.8489	.000163	.0000462
		O	0.0000	.000000	.0000
8	Graphite	C	1193.9254	.068185	.019365
		N	80.6727	.004607	.001309
		O	0.0014	.000000	.000000
TOTAL: 17508.6672 (Cell 8)					.283991
17505.7487 (Cell 23)					.283943
<u>Cell 13 and 18 (Target)</u>					
1	Target	B	728.8110	.136506	.011821
2	Target clad	Al	1476.5060	.276550	.02395
3	Water	H	817.4869	.153115	.01326
		O	0.2637	.000049	.00000
4	Process tube	Al	1133.9597	.212391	.01839
5	Air	N	20.0716	.003759	.00033
		O	0.0003	.000000	.00000
6	Graphite	C	1092.5835	.204641	.01772
		N	73.8252	.013827	.00120
		O	0.0012	.000000	.00000
TOTAL: 5339.5091 (Cell 13)					.086607
5339.5091 (Cell 18)					.086607

TABLE XExperimental 1/v Absorption Rates and Utilizations
(Lattice Without Coolant)

<u>No.</u>	<u>Region</u>	<u>Isotope</u>	<u>(Abs)1/v</u>	<u>Cell 1/v Utilization</u>	<u>Unpoisoned Supercell 1/v Utilization</u>
<u>Cell 3 (Fuel)</u>					
1	Air	N	0.18605	.000016	.000004
		O	0.00001	.000000	.000000
2	Fuel inner clad	Al	57.3885	.004938	.001302
3	Fuel	²³⁵ U	7328.423	.630562	.166260
		²³⁸ U	3212.206	.276389	.072875
4	Fuel outer clad	Al	207.68812	.017870	.004712
5	Air	N	1.05985	.000091	.000024
		O	0.00002	.000000	.000000
6	Process tube	Zr	46.0262	.003960	.001044
7	Air	N	1.43094	.000000	.000032
		O	0.00002	.000000	.000000
8	Graphite	C	719.0466	.061869	.016313
		N	48.5867	.004181	.001102
		O	0.00082	.000000	.000000
		TOTAL:	11,622.0427		.263669
<u>Cells 8 and 23 (Fuel)</u>					
1	Air	N	0.24503	.000018	.000006
		O	0.00001	.000000	.000000
2	Fuel inner clad	Al	75.3900	.005621	.001710
3	Fuel	²³⁵ U	8401.8790	.626435	.190613
		²³⁸ U	3726.1723	.277819	.084536
4	Fuel outer clad	Al	253.3182	.018887	.005747
5	Air	N	1.28353	.000096	.000029
		O	0.00002	.000000	.000000
6	Process tube	Zr	55.93755	.004171	.001269
7	Air	N	1.74337	.000130	.000040
		O	0.00003	.000000	.000000
8	Graphite	C	839.24314	.062573	.019040
		N	57.00712	.004250	.001293
		O	0.00096	.000000	.000000
		TOTAL:	13,412.2199 (Cell 8)		.304283
			13,409.8670 (Cell 23)		
<u>Cell 13 and 18 (Target)</u>					
1	Target	B	561.7404	.162395	.012744
2	Target clad	Al	1144.3120	.330813	.025961
3	Air	N	0.21668	.000062	.000005
		O	0.00004	.000000	.000000
4	Process tube	Zr	876.0204	.253152	.019874
5	Air	N	1.53985	.000445	.000035
		O	0.00026	.000000	.000000
6	Graphite	C	819.5868	.236937	.018594
		N	55.6720	.016094	.001263
		O	0.00094	.000000	.000000
		TOTAL	3459.0897 (Cell 13)		.078476
			3459.0897 (Cell 18)		.078476

TABLE XISummary of Absorption DataSupercell With Coolant:

Sum of 1/v Utilization:

Cell 3	11,622.043
Cell 8	13,412.220
Cell 13	3,459.090
Cell 18	3,459.090
Cell 23	13,409.867
TOTAL	45,362.309

Poison - 2140.414

$f = .76703$

$f' = .80501$

Supercell Without Coolant:

Sum of 1/v Utilization:

Cell 3	15,937.587
Cell 8	17,508.667
Cell 13	5,339.509
Cell 18	5,339.509
Cell 23	17,505.749
TOTAL	61,631.021

Poison - 7538.857

$f = .71187$

$f' = .81109$

G. Determination of k_{∞} from These Experiments

In the case of uranium fuel with a simple $1/v$ absorber target, the equations for calculating k_{∞} can be reduced to the familiar four factor formula,⁽⁷⁾

$$k_{\infty} = \eta \epsilon p f \quad (7)$$

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

$$k'_{\infty} = \eta \epsilon p f' = 1 \quad (8)$$

Therefore, k_{∞} of the supercell has been derived^(2,3) as the ratio of the unpoisoned to poisoned thermal utilizations.

$$k_{\infty} = \frac{f}{f'} \quad (9)$$

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

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

This derivation of $f_{1/v}$ is (Equation 11) 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 using the flux measured by a detector whose absorption cross section values as $1/\sqrt{E}$ multiplied by the effective 2200 m/sec cross section calculated from 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 for the derivation of $k_{\infty 1/v}$ implies that,

$$k_{\infty} = \eta_{1/v} \epsilon p_{\text{non-}1/v} f_{1/v} \quad (10)$$

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

Equation (1) can be rewritten in terms of absorption rates by use of Equation 11;

$$k_{\infty}-1 = \frac{(\text{Abs})'_p}{\sum_i (\text{Abs})'_i} + \frac{\sum_i [(\text{Abs})'_i - (\text{Abs})_i]}{\sum_i (\text{Abs})_i} \quad (11)$$

$(\text{Abs})'_p$ = 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 equation 11 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 the supercell is negative for both the lattice with and without coolant, the copper could not be added in negative amounts. Therefore, the quantities $(\text{Abs})'_i = (\text{Abs})_i$, and equation (11) reduces to:

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

Values of k_{∞} determined from these PCTR experiments are presented in Table I. Again, it should be noted that the values in Table I are highly dependent upon reactivity measurements with the large supercell removed. Neutron streaming was sure to exist between the PCTR drivers nearest the top and bottom of the supercell. These perturbation effects are illustrated in the inability to determine the mass of copper for M_0 within ± 150 gm. and which are the primary cause of the errors in each measurement.

V. CORRECTIONS AND SYSTEMATIC ERRORS

A. Nitrogen Correction

During the reactivity measurements the nitrogen in the reactor has a two-fold effect: the air is in the void space in the graphite during the cell-in measurements, and air fills the cavity during the measurements with the supercell out.

Determination of the reactivity worth of the nitrogen which fills the cavity formed by the removal of the central supercell is inferred from a copper sensitivity measurement using the expression,

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

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

$$S_{Cu}^{cavity} = \frac{\Delta\rho_{Cu}^{cavity}}{M_{Cu \text{ in cavity}}} , \phi/\text{gm of copper}$$

$\Delta\rho_{Cu}^{cavity}$ = worth of a mass of copper, M_{Cu}^{cavity} , in the supercell cavity, ϕ .

P = atmospheric pressure during reactivity measurement, mb.

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

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

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

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

$\sigma_o^{Cu} = 2200$ m/sec microscopic absorption cross section of natural copper = 3.79 b.

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 if natural copper, approximated by:

$$(1-c) = 1 - \left(\frac{m_1}{m_2} \right) \frac{RI_{ex}^{Cu}}{RI_{epi-Cd}^{Cu} (CDR-1)} \quad (12)$$

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 calculated by MOFDA. (10)

RI_{ex}^{Cu} = effective excessive resonance integral of natural copper for the thickness of copper used in measuring $S_{Cu}^{cavity} = 1.3705$. (4)

RI_{epi-Cd}^{Cu} = effective epi-cadmium resonance integral of natural copper for the thickness of copper and in measuring $S_{Cu}^{cavity} = 2.8805$. (4)

CDR = cadmium ratio of copper in the cavity for the thickness of copper used in measuring $S_{Cu}^{cavity} = 13.7$

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

The requirement that the material used as the absorber in the determination of $k_{\infty} 1/v$ 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 the reactivity coefficient is equivalent to the correct mass of copper, M_o .

$$M_{1/v} SA_{1/v} m_2 = M_o (SA_{1/v} m_2 + SA_{res} m_1) \quad (13)$$

Account is taken of the worth of epithermal 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⁽¹¹⁾ that,

$$M_{1/v} = M_0 \left[1 + \left(\frac{m_1}{m_2} \right) \left(\frac{RI_{Cu}^{ex}}{CDR \cdot RI_{epi-Cd}^{Cu} - RI_{ex}} \right) \right] \quad (14)$$

Copper strips 0.003" thick were inserted at the boundary of the supercell, and the cadmium ratio of the copper at the boundary was measured with 0.003" copper foils inserted in these strips. Effective resonance integrals for 0.003" thick natural copper were taken from measurements by Bennett.⁽⁴⁾ Values for $M_{1/v}$ are only a few percent greater than M_0 and are included in Tables V and VI.

C. 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 reactivity measurement of the cell-out if neutron streaming from the cavity to these ends is appreciable.

The center cell and end buffer cell were exchanged during a series of null reactivity measurements to determine the effect of a shorter center cell in the matched spectrum. The correct mass of copper required to absorb the excess neutrons of the central supercell per unit length of center cell did not indicate any change.

In other words, the end effects with supercells containing bismuth were practically negligible as determined in this experiment. Previous experiments

using lithium targets indicated the end effects to be as much as 5.7 mk (12) which proves that this effect is also a function of the blackness of the material in the cell and therefore unapplicable with the bismuth target elements.

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3 - Battelle-Memorial Institute

TABLE XISummary of Absorption DataSupercell With Coolant:

Sum of 1/v Utilization:

Cell 3	11,622.043
Cell 8	13,412.220
Cell 13	3,459.090
Cell 18	3,459.090
Cell 23	13,409.867
TOTAL	45,362.309

Poison - 2140.414

f = .76703

f' = .80501

Supercell Without Coolant:

Sum of 1/v Utilization:

Cell 3	15,937.587
Cell 8	17,508.667
Cell 13	5,339.509
Cell 18	5,339.509
Cell 23	17,505.749
TOTAL	61,631.021

Poison - 7538.857

f = .71187

f' = .81109