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MEASUREMENT OF THE TEMPERATURE
DEPENDENCE OF K_{∞} FOR A
 $^{233}\text{UO}_2$ - ThO_2 HTGR LATTICE

E. P. Lippincott

May 1971

AEC RESEARCH &
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PACIFIC NORTHWEST LABORATORIES

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By

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ABSTRACT

The second in a series of experiments using the High Temperature Lattice Test Reactor has been completed and provides information on the temperature dependence of k_{∞} for a $^{233}\text{UO}_2 - ^{232}\text{ThO}_2 - \text{C}$ fuel mixture. The infinite medium multiplication factor, was found to decrease by $.0350 \pm .0015$ from 20°C to 1000°C . This result provides direct information necessary in the design of the control system and in the safety analysis for advanced High-Temperature Gas-Cooled reactors.

Acknowledgements

Many people have contributed to the successful completion of this experiment. In particular, many helpful discussions with J. C. Peak, R. C. Dahlberg, J. R. Brown, and D. Mathews of the Gulf General Atomic Company assured that the experimental design closely duplicated the reference HTGR lattice designs.

Reimar Froelich made significant contributions to the theoretical basis for the method of experimental analysis. The strong support provided by the HTLTR operating staff, and helpful discussions with T. J. Oakes, C. R. Richey, and D. F. Newman, also contributed significantly to the success of the experiment.

I. INTRODUCTION

The second experiment of a series of experiments in the High Temperature Lattice Test Reactor (HTLTR) is described in this report. This series is designed to measure nuclear data of interest in the High Temperature Gas Cooled Reactor (HTGR) program. Data from these experiments are of direct use in the design and safety analysis of advanced high temperature gas cooled reactors.

The lattice in the first experiment in this series contained thorium and ^{235}U fuel.⁽¹⁾ Measurements made on that lattice included the total temperature coefficient, the Doppler coefficient, and the temperature coefficient of the reactivity worth of several poison materials of interest. In the second lattice, the amount of thorium was kept unchanged but ^{233}U was substituted for the ^{235}U . In this case the Doppler coefficient is relatively unchanged and was not remeasured, but the other temperature coefficients were measured as in the first lattice. The neutron spectrum in the second lattice was more thermal since less fissile material was present in the test fuel.

The ^{233}U experiment was carried out in two parts. First, the lattice was loaded into the Physical Constants Test Reactor (PCTR) for measurements at room temperature. The PCTR is similar to the HTLTR but has a movable face allowing easy access to the

center of the reactor, thus permitting greater flexibility in the measurement of small reactivity effects. In addition, this greater accessibility, together with the presence of a thermal column for normalization, allow much easier and more accurate foil irradiations to be made.

The second part of the experiment was carried out in the HTLTR. A brief program of room temperature measurements was performed to assure consistency between PCTR and HTLTR results, followed by an extensive program of measurements at elevated temperatures, up to and including 1000°C.

The results obtained from the experiments include reactivity worths at each temperature for the test cell and for various special sample materials. The PCTR results were used to evaluate k_{∞} at room temperature and analytical calculations together with the HTLTR results enable k_{∞} to be obtained at the elevated temperatures.

II. PRINCIPLE OF THE MEASUREMENT

The principle result of the HTLTR experiments is the determination of the infinite-medium neutron multiplication factor, k_{∞} , as a function of temperature. The factor obtained is not that for a true infinite medium, but rather that for a bare critical reactor. Thus k_{∞} is evaluated for fluxes in the fundamental mode.

To avoid ambiguity, k_{∞} is defined by

$$k_{\infty} = \frac{\text{total production}}{\text{total absorption}}. \quad (1)$$

In the two energy group approximation, this becomes

$$k_{\infty} = \frac{\nu_1 \Sigma_1^f \phi_1 + \nu_2 \Sigma_2^f \phi_2}{\Sigma_1^a \phi_1 + \Sigma_2^a \phi_2} \quad (2)$$

where subscript 2 represents the thermal region and 1 represents the epithermal region. These quantities are also related by the two-group equations:

$$-D_1 B^2 \phi_1 - \Sigma_1^a \phi_1 - \Sigma_{12} \phi_1 + \nu \Sigma_1^f \phi_1 + \nu \Sigma_2^f \phi_2 = 0 \quad (3a)$$

$$-D_2 B^2 \phi_2 - \Sigma_2^a \phi_2 + \Sigma_{12} \phi_1 = 0 \quad (3b)$$

where Σ_{12} is the cross section for transfer from group 1 to group 2 and B^2 is the buckling.

The measurement in the HTLTR is carried out by the unpoisoned technique.⁽²⁾ In this technique a small representative sample of the type of lattice to be investigated (known as a central cell) is inserted into a void in the center of the reactor. Surrounding this void is a region of material similar to the central cell, and the fluxes in this region are adjusted to be as close as possible to the fundamental mode fluxes. The reactivity perturbation caused by the insertion of the central cell is normalized to the perturbation where a sample of copper is placed in the void. It is also necessary to measure the rate of neutron absorption in the copper and central cell.

Using first order perturbation theory,⁽²⁾ and equations (2) and (3) above, the following relationship between k_{∞} and the measured quantities may be derived,^(3,4)

$$\begin{aligned}
 k_{\infty} = & 1 - \frac{\Delta\rho^{\text{cell}}}{\Delta\rho^{\text{P}}} \frac{(\sum_2^{\text{PV}} \phi_2^{\text{P}})}{(\sum_2^{\text{AV}} \phi_2^{\text{P}})_{\text{cell}}} (1+\alpha) - \frac{(1+\tau B^2)(1+L^2 B^2)(1-p)L^2 B^2}{1+(1-p)L^2 B^2} \\
 & + \frac{\tau B^2(1+L^2 B^2) \left[\tau B^2 - \eta_1 f_1 (1-p) \right]}{1 + \tau B^2 - \eta_1 f_1 (1-p)} - \frac{\tau B^2(1+L^2 B^2)}{1 + \tau B^2 - \eta_1 f_1 (1-p)} \left(\frac{\Delta\Phi}{\Phi} + \frac{\Delta\Phi^+}{\Phi^+} \right) \\
 & + \frac{(1+L^2 B^2)(1 - \eta_1 f_1 (1-p))}{1 + \tau B^2 - \eta_1 f_1 (1-p)} \frac{\Delta\Phi}{\Phi} - \frac{\Delta\Phi^+}{\Phi^+}
 \end{aligned} \tag{4}$$

In equation (4), $\Delta\rho^{\text{cell}}$ and $\Delta\rho^{\text{P}}$ represent the reactivity changes due to insertion of the central cell or poison into the void, respectively. $(\sum_2^{\text{AV}} \phi_2^{\text{P}})$ represents the actual thermal neutron

absorptions in the central cell. The quantity a is a correction for the epithermal absorptions in the copper and is discussed further in Appendix A. ϕ is defined as ϕ_1/ϕ_2 and $\Delta\phi$ is the difference between ϕ for the fundamental mode and the ϕ actually present with the cell in. ϕ^+ is defined similarly for the adjoint fluxes except $\Delta\phi^+$ is evaluated at the surface of the void. The remaining parameters are defined as follows,

$$\tau = \frac{D_1}{\Sigma_1^a + \Sigma_{12}} \quad (5)$$

$$L^2 = \frac{D_2}{\Sigma_2} \quad (6)$$

$$\eta_1 f_1 = \frac{v \Sigma_1^f}{\Sigma_1^a} \quad (7)$$

$$p = \frac{\Sigma_{12}}{\Sigma_{12} + \Sigma_1^a} \quad (8)$$

From equations (2) and (3) it may be shown that

$$k_\infty = \frac{(1 + \tau B^2)(1 + L^2 B^2)}{1 + (1-p) L^2 B^2} \quad (9)$$

Since the buckling is not measured experimentally and cannot be accurately calculated, equation (9) is used to eliminate B^2 from equation (4). Equation (4) may be written as

$$k_\infty - 1 = A - a_1 B^2 - a_2 B^4 \quad (10)$$

to second order in B^2 , where

$$A = -\frac{\Delta\rho^{\text{cell}}}{\Delta\rho^p} \frac{\left(\frac{\tau^p}{\Sigma_2^{\phi} V}\right)^p}{\left(\Sigma_2^{\phi} V\right)^{\text{cell}}} \left(1 + a\right) + \frac{\Delta\phi}{\phi} \frac{\Delta\phi^+}{\phi^+} \quad (11)$$

$$a_1 = L^2(1-p) + \frac{\tau\eta_1 f_1(1-p)}{1-\eta_1 f_1(1-p)} + \frac{\tau}{1-\eta_1 f_1(1-p)} \left(\frac{\Delta\phi}{\phi} + \frac{\Delta\phi^+}{\phi^+}\right) \quad (12)$$

$$\begin{aligned} & - \frac{L^2 \left[1-\eta_1 f_1(1-p)\right] - \tau \frac{\Delta\phi}{\phi} \frac{\Delta\phi^+}{\phi^+}}{1 - \eta_1 f_1(1-p)} \\ a_2 = & (1-p)L^2(\tau+pL^2) - \frac{\tau}{1-\eta_1 f_1(1-p)} \cdot \left[\frac{\tau}{1-\eta_1 f_1(1-p)} - L^2\eta_1 f_1(1-p) \right] \quad (13) \\ & + \frac{\tau L^2 (1-\eta_1 f_1(1-p)) - \tau^2}{\left[1-\eta_1 f_1(1-p)\right]^2} \left(\frac{\Delta\phi}{\phi} + \frac{\Delta\phi^+}{\phi^+}\right) - \frac{\tau L^2 \left[1-\eta_1 f_1(1-p)\right] + \tau^2}{\left[1-\eta_1 f_1(1-p)\right]^2} \frac{\Delta\phi}{\phi} \frac{\Delta\phi^+}{\phi^+} . \end{aligned}$$

Solving for B^2 to second order from Equation (9), substituting in (10) and inverting the series to solve for $k_\infty - 1$ results in

$$k_\infty - 1 = b_1 A + b_2 A^2, \quad (14)$$

where

$$b_1 = \frac{\tau + pL^2}{a_1 + \tau + pL^2} \quad (15)$$

and

$$b_2 = \frac{-a_2(\tau+pL^2) + a_1 pL^2 \left[\tau - L^2(1-p)\right]}{(\tau+pL^2 + a_1)^3} \quad (16)$$

To first order, $k_\infty - 1$ is given by

$$\begin{aligned} k_\infty - 1 = & \frac{A}{1 + \frac{1}{\tau+pL^2} \left[(1-p)L^2 + \frac{\tau\eta_1 f_1(1-p)}{1-\eta_1 f_1(1-p)} + \frac{\tau}{1-\eta_1 f_1(1-p)} \left(\frac{\Delta\phi}{\phi} + \frac{\Delta\phi^+}{\phi^+}\right) \right.} \\ & \left. - \frac{L^2 \left[1-\eta_1 f_1(1-p)\right] - \tau \frac{\Delta\phi}{\phi} \frac{\Delta\phi^+}{\phi^+}}{1-\eta_1 f_1(1-p)} \right] \quad (17) \end{aligned}$$

III. DESCRIPTION OF FUEL

A. Fuel Blocks

In the HTGR lattice the fuel and moderator are both contained in the fuel block. A typical block, illustrated in Figure 1, is a 3-3/4-inch by 3-3/4-inch square by 24-inch long graphite bar (SGBF graphite). The absorption cross section of this graphite is about 3.80 mb in an air atmosphere. The graphite block contains 25 channels, 0.470-inches in diameter, in a 5 x 5 array. Each channel was closed at each end with a threaded graphite plug 0.5-inch in length, resulting in a fuel channel 23-inches in length. In drilling the fuel channels some drill wander is unavoidable but the effect of this was minimized by drilling the blocks from both ends and by selecting the best blocks for use as the central cell.

The fuel consisted of a blend of $^{233}\text{UO}_2$ - ThO_2 particles, ThO_2 , and graphite. The $^{233}\text{UO}_2$ - ThO_2 particles contain 1 part $^{233}\text{UO}_2$ and 3 parts ThO_2 in a microsphere core which is enclosed in a pyrocarbon coating. These particles were specially prepared at Oak Ridge National Laboratory (ORNL). According to the ORNL characterization report, the mean microsphere diameter is 280 μ with a standard deviation of 30 μ and the mean coating thickness is 100 μ . These

FIGURE 1: SIMULATED HTGR FUEL ELEMENTS

particles were prepared in batches and there is some quoted variation from batch to batch. The numbers quoted above are for the batch of particles used in the central cell of the test lattice. The overall mean particle diameter for all the blocks is 290 μ .

The amount of ^{233}U and Th in each batch of particles was measured chemically by ORNL. These measurements have an estimated accuracy of 1%. Therefore, although the total weight of particles in each block is accurately known, the amount of ^{233}U in each block has a 1% uncertainty. A much smaller uncertainty exists for the amount of thorium in each block.

The thoria particles consist of irregular shapes of various sizes. The distribution of sizes by weight as determined by screening a small sample is given in Table I.

The graphite particles were prepared by collecting particles milled from nuclear grade graphite blocks. These particles were then separated into two size portions by screening. Half the graphite particles used were less than 210 μ (-65 mesh) and the other half were 350 μ to 590 μ . (-28 mesh + 42 mesh).

TABLE I
THORIA PARTICLE SIZE DISTRIBUTION

Screen Size	Particle Size Range (μ)	Weight Percent
100 - 65	149 - 210	11.1
150 - 100	105 - 149	3.7
200 - 150	74 - 105	19.4
325 - 200	44 - 74	16.4
-325	0 - 44	49.4

In addition to the standard blocks, special blocks were necessary. The blocks for the HTLTR fuel train were constructed to be coupled together. This necessitated inserting end caps in 10 of the fuel channels to 1.3 inch instead of 0.5 inch. Modified blocks were also necessary to support the region over the central cell to permit its removal. These blocks had 0.25 inch of graphite removed from 10 channels to enable a crosspiece of graphite to be inserted as a support. These 10 channels then had end plugs inserted to 0.75 inch instead of 0.5 inch.

B. Loading of Fuel Blocks

To load the fuel blocks, the $^{233}\text{UO}_2$ - ThO_2 particles, ThO_2 and each of the two graphite particle sizes were weighed separately in amounts sufficient to fill one fuel block plus 10%. One end of the fuel block was sealed with half-inch long graphite end plugs screwed in flush with the block surface. The fuel was loaded in the other end through a specially constructed funnel with 25 holes. During the loading the block was set in a vertical position on a vibrator which was used to compact the fuel mixture into the channels. After vibration, the excess fuel blend was removed and the open end sealed with graphite end caps. The finished blocks thus contain 23 inches of fuel blend in each channel and 0.5 inch of graphite on each end.

Using the above method for loading fuel blocks leads to small variations in the amount of material in each block. These variations mainly occur because of small differences between the blocks (i.e. the exact way in which the holes were drilled) and the differences between the way the fuel material packs into each hole. These variations were kept to a minimum and in particular, the blocks used for the central cells were carefully selected and extra care was taken with the fuel loading. Of the remaining blocks, each was characterized by the C/Th ratio and the total thorium in the block. Blocks within specifications but differing significantly from the mean loading were placed into the reactor at the outer edge of the buffer region. Blocks whose loadings came closest to the mean value were placed in the vicinity of the central cell insofar as possible.

The loading procedure described above was developed in an attempt to achieve a homogeneous fuel distribution throughout each fuel channel. In order to develop the loading procedure, various methods were tried using a special block with 1 x 5 channels. Various graphite size fractions were tried before the final blend was adopted. Each loading of the special block was x-rayed and the x-ray was visually inspected to determine the ThO₂ and ²³³U particle distribution. After the 1 x 5 block had been loaded consistently with the fuel particles well distributed, a full block was loaded and x-rayed as an overall check.

C. Description of Central Cell Blocks

Two sets of central cell blocks were used. In the PCTR the central cell consisted of four standard blocks with 0.005 inch of graphite removed from the outer edge to allow room for insertion. The composition of these four blocks is described in Table II.

The composition of the blocks in the central cell in the HTLTR is described in Table III. These four blocks were coupled to the cell train at one end for remote removal. The end towards the front of the reactor was standard. These blocks were shaved 0.010-inch to allow for insertion

D. Special Samples

Special poison blocks, the reactivity worths of which were measured in the ^{235}U HTGR experiment were used again in the ^{233}U lattice. The contents of these blocks is presented in Table IV. The poison blocks are similar to the fuel blocks except for the replacement of the normal fuel mixture with neutron absorber material mixed with graphite. The blocks were loaded in a manner similar to the fuel blocks.

TABLE II
COMPOSITION OF PCTR CENTRAL CELL

Block #	Composition in Grams					Atoms/Barn-Cm Average (Each Region)
	57	66	76	77	Total	
Moderator Region						
Volume Total = 15583.6 cm ³						
Carbon	6188.8	6299.2	6208.5	6428.2	25124.7	.08088
Nitrogen	1.33	1.27	1.32	1.20	5.12	.00001412
Fuel Region						
Volume Total = 6539.9 cm ³						
Carbon Particles	1534.2	1527.7	1519.7	1514.0		
Pyrocarbon	54.1	53.8	53.6	53.4		
Total	1588.3	1581.5	1573.3	1567.4	6310.5	.04841
Thorium ²³³ U Particles	42.62	42.44	42.22	42.06	169.34	
ThO ₂ Particles	712.95	709.94	706.24	703.57	2832.70	
Total	755.57	752.38	748.46	745.63	3002.04	.001191
Nitrogen	1.05	1.06	1.06	1.06	4.23	.00002782
²³³ U	13.97	13.91	13.84	13.79	55.51	.00002193
²³⁴ U	.150	.150	.149	.148	.597	2.35x10 ⁻⁷
²³⁵ U	.012	.012	.012	.012	.049	1.9x10 ⁻⁸
²³⁶ U	.001	.001	.001	.001	.004	0.2x10 ⁻⁸
²³⁸ U	.192	.191	.190	.189	.763	2.95x10 ⁻⁷
Oxygen	106.2	105.7	105.2	104.8	421.9	.002428

TABLE III
COMPOSITION OF HTLTR CENTRAL CELL

		Composition in Grams				Total
		105	107	108	109	
Moderator Region						
	Carbon	6251.7	6261.7	6214.4	6388.6	25116.4
	Nitrogen	1.32	1.31	1.34	1.25	5.22
Fuel Region						
	Carbon: Particles	1488.8	1505.3	1506.4	1492.3	
	Pyrocarbon	52.5	52.8	53.1	52.6	
	Total	1541.3	1558.1	1559.5	1544.9	6203.8
	Nitrogen	.97	.97	.97	.97	3.88
	^{233}U	13.56	13.64	13.72	13.59	54.51
	^{234}U	.146	.147	.147	.146	.586
	^{235}U	.012	.012	.012	.012	.048
	^{236}U	.001	.001	.001	.001	.004
	^{238}U	.186	.187	.188	.187	.749
	Oxygen	103.0	104.2	104.3	103.3	414.8
	Thorium: ^{233}U Particles	41.36	41.81	41.85	41.45	
	ThO_2 Particles	691.85	699.52	700.04	693.48	
	Total	733.21	741.33	741.89	734.93	2951.36

TABLE IV

COMPOSITION OF POISON BLOCKS

<u>Poison</u>	Amount of Poison (gm. of element)	Total Block Weight (gm)
Eu	1.96	7888
Sm	1.67	7718
Gd*	1.69*	7722
Hf	82.3	7926
Rh	44.4	7824

*rare earth mixture containing approximately 50% Gd_2O_3 mixed with other rare earths (mostly Sm_2O_3); weight shown is total rare earth. The cross section at room temperature is at least 80% due to Gd.

IV. PCTR Experiment

A. Spectrum-matching Measurements

The fuel blocks were loaded in the PCTR in an 8 by 8 array. For the buffer region at the ends, special short fuel blocks were constructed to fit at the front and rear of the four central cell blocks and the twelve adjacent blocks. The space at the ends of the remaining forty-eight blocks was filled with standard HTGR blocks laid across horizontally and vertically, and with graphite bars. The complete lattice, as installed in the PCTR, is shown in Figure 2.

In order to match the flux spectrum incident on the central cell to the equilibrium value (i.e. the fundamental mode value), the gold cadmium ratio was measured radially and axially. The lattice is considered matched if ϕ_1/ϕ_2 is adjusted to be constant throughout the region adjacent to the central cell. In addition, to minimize streaming, the flux is flattened in the axial direction.

FIGURE 2: PCTR LOADING - HTGR LATTICE

The initial loading with a single natural uranium element in each position in the buffer region resulted in a slightly over-thermalized spectrum, i.e., the cadmium ratio increases with distance from the center of the reactor. An average over the central cell compared to two blocks farther out was used as a criterion to determine the match. This criterion indicated a radial mismatch of 5.2%. The axial match was more difficult to determine due to the asymmetry created by the end caps. The flux at the peak in the end cap region, as measured by a copper absorber, was found to be about 8% higher than at the center of the block. A comparison made between the cadmium ratio at the center of the block and that in the end buffers indicated that the flux was about 0.4% harder (less thermal) in the end buffers, and this was considered a good match.

The addition of another natural uranium element and a copper-jacketed mixed oxide element to each position in the buffer in order to harden the flux resulted in the flux being 0.3% hard radially and 0.7% hard axially, using the above criterion. A later irradiation was made with this loading to obtain improved data, and at this time the radial match was 0.7% hard and the axial 1.7% hard.

B. Reactivity Measurements

Reactivity measurements of central cell and copper worth were made for each of the loadings described above. Little difference was observed, indicating that an exact flux match is not necessary.

The results of the PCTR reactivity measurements are summarized in Table V. In addition to measurements of the central cell and copper worths, also measured were the graphite worth in the void, the worth of the HTLTR central cell, and the worth of graphite equivalent to the PCTR central cell and HTLTR central cell end cap regions. The errors quoted in Table 5 are estimated from the repeatability of the measurements on the HTGR lattice. From these measurements, the value of the mass of copper needed to reduce the central cell reactivity worth (including end caps) to zero was found to be 318.0 ± 2.2 grams.

TABLE V

Relative Reactivity Worths in the PCTR

PCTR Central Cell	$10.24 \pm 0.04\phi$
Copper in void	$0.0322 \pm 0.0002\phi/\text{gram}$
Graphite in void	$0.795 \pm 0.029\phi/\text{kg}$
HTLTR Central Cell	$10.98 \pm 0.06\phi$
PCTR end caps	$1.74 \pm 0.05\phi (1.05\phi/\text{kg})$
HTLTR end caps	$2.10 \pm 0.07\phi (1.00\phi/\text{kg})$

The incremental graphite worth was measured by placing two pieces $2\frac{1}{4}$ inch x $1\frac{1}{4}$ inch x $3\frac{3}{4}$ inch at the bottom of the void. The graphite equivalent to the end caps was measured by placing dummy graphite pieces at the ends of the void. For the standard cells, these consisted of eight pieces $3\frac{3}{4}$ inch x $3\frac{3}{4}$ inch x $1\frac{1}{2}$ inch. For the HTLTR central cell end caps, the pieces at one end had extensions to 1.3 inch to account for the extra graphite used for the coupling. The graphite for the PCTR dummy end caps weighed 1656.65 gm. and that for the HTLTR, 2092.56 gm. From the reactivity measurements, it is seen that the end cap graphite is worth about 30% more per gram than the graphite placed uniformly along the length of the void.

A reactivity check was also made of each of the four central cell blocks. By removing each of these blocks from the reactor singly, the variation among the blocks was measured. This variation was found to be 4.7%. After correcting for the difference in graphite weight among the blocks, this difference was reduced to 2.4% which is about the limit of error of the measurement. Thus, an uncertainty of less than this magnitude would be expected in $k_{\infty}-1$ due to variations in fuel loading in the block.

C. Measurement of Absorptions in the Central Cell

In order to measure the rate of thermal neutron absorptions in the central cell relative to the absorptions in the copper poison in the void, (required in Equation 4 to determine k_{∞}) foil activations were used. Both bare (total) and cadmium-covered (epithermal) activities were measured and the thermal activity was determined by subtraction. Since relative absorption rates are required, each foil irradiated in the reactor was normalized to a similar foil irradiated in the PCTR thermal column. The thermal column foils were mounted on a rotator so that each foil was exposed to an identical flux. Normalizing the foils in this manner eliminates all effects due to counting efficiency and geometry.

The foil irradiations to determine the cell absorptions were carried out using the special fuel block shown in Figure 3. This block had the fuel in two channels contained in removable aluminum cylinders, three in each channel, between which foils could be inserted. Special foils were constructed to fit in the fuel channels. Foils made of copper, thorium metal, and foils containing a mixture of ^{233}U , thorium, and graphite identical to the fuel were used. The latter two foils were used to evaluate the absorptions in ^{233}U and thorium. The copper foils were used to integrate the flux over the cell and evaluate the absorptions in the other cell components.

FIGURE 3: SPECIAL HTGR FUEL BLOCK USED IN FOIL IRRADIATIONS

Four different irradiations were made. These included bare and cadmium covered foil irradiations to evaluate the absorptions in the copper poison in the void, and bare and cadmium-covered irradiations with foils in the fuel block. The copper and ^{233}U were counted using a NaI detector and a single channel analyzer. The data was analyzed using APDAC,⁽⁵⁾ a code which corrects for decay and background. The thorium activations were measured using a NaI detector and also using a Ge(Li) detector, together with a multichannel analyzer. Corrections for background and decay were hand calculated.

The copper and thorium foils were normalized by weight. The copper foils used to evaluate the copper absorption in the void were 0.010 inch thick as was the copper used in the reactivity measurements. For the cell absorption, the copper foils used were .005 inch thick and the thorium foils were 0.002 inch thick. The $^{233}\text{UO}_2 - \text{ThO}_2 - \text{C}$ fuel foils were constructed by enclosing a small amount of carefully weighed fuel in a small aluminum can, about .100 inch in thickness. Because of the small amount of material involved, foils had to be normalized by a separate irradiation. The normalization was carried out by exposing the foils to a thermal flux in the Thermal Test Reactor. Both the thorium and ^{233}U in these foils were normalized in this manner.

In order to correct the foil data for perturbations caused by the foils and cadmium covers, an analysis was made using the two-dimensional transport code DOT.⁽⁶⁾ A four group calculation was done using cross sections generated by EGGNIT⁽⁷⁾ and THERMOS.⁽⁸⁾ From this calculation it was concluded that the thermal flux perturbations due to the foils and aluminum were negligible. However, the cadmium covers perturbed the adjacent thermal flux and caused a 3.3% decrease in the epithermal flux seen by the foils. All of the measured cadmium-covered foil data were therefore increased by a factor of 1.033.

The integral of the absorptions throughout the cell was determined using copper foils. The axial copper flux traverse is shown in Figure 4 and is compared with the result of a calculation done with the one-dimensional transport code DTF-IV.⁽⁹⁾ Two energy groups were used in the calculation with cross sections generated by EGGNIT and GRANIT⁽¹⁰⁾ (these calculations are described further in Section VII). Two regions were used in a slab geometry, a homogeneous cell region and a graphite region for the end caps. Good qualitative agreement between calculation and experiment was obtained,

FIGURE 4: CENTRAL CELL AXIAL COPPER FLUX TRAVERSE

with the difference in magnitude of the peaking of the flux at the cell ends probably due to the error in axial flattening of the flux. In addition to the axial variation, a small radial variation in flux over the central cell was also measured. The measurement of the flux depression in the fuel was also attempted but this was found to be less than 1% (as measured by copper).

The corrected activity data averaged over the cell and the copper absorptions derived from these data are presented in Table VI. Significant errors are also presented. The errors in the copper measurements are small relative to each other and involve about 1% absolute error. The ^{233}U activations required a foil normalization and also have an inherent error in being small samples of the fuel. The error in these activity measurements is therefore slightly larger, about 1.5%. In addition an error of 1% in the ^{233}U absolute weight is included.

The errors in the thorium activation are even larger because of the low cross section and long half life. The main difficulty was in activating the monitor foil sufficiently to obtain enough counts above the high residual background of the thorium. The error in these activations is estimated to be about 2%. Errors in thermal activities are larger because these are obtained by subtracting the cadmium-covered activity from the total activity.

TABLE VI

Evaluation of Cell and Copper Absorptions

<u>Component</u>	<u>Weight (gm)</u>	<u>Atomic Wt.</u>	$\sigma_{\text{Thermal Col}}^{2200}$ <u>(barns)</u>	<u>Activity</u>	<u>Relative Absorptions</u>
<u>CELL OUT</u>					
Copper - Thermal	1.0	63.54	3.75	4.980	.294 $\pm$.003
Epithermal			(.010-in)	.627	.037
<u>CELL IN</u>					
<u>Thermal</u>					
^{233}U	55.51 $\pm$.56	233.	551.7	5.066*	665.8 $\pm$ 13.8
^{232}Th	3002.0	232.	7.37	4.813	459.0 $\pm$ 11.3
C	31433.0	12.	.0035	5.055**	46.34 $\pm$.54
O	421.7	16.	.0002	5.055**	.03
N	9.00	14.	1.85	5.055**	6.01
^{235}U	0.0048	235.	636.1	5.055**	.07
^{234}U	0.593	234.	91.33	5.055**	1.17
^{238}U	0.749	238.	2.62	5.055**	.04
Total					1178.4 $\pm$ 18.0
<u>Epithermal</u>					
^{233}U	55.51	233.	---	1.083*	142.5 $\pm$ 3.2
^{232}Th	3002.0	232.	---	5.095	485.9 $\pm$ 12.8
Rest of Cell	---	---	---	.256**	2.72
Total					631.1

*Corrected to absorption activation using calculated values for Σ_f/Σ in the cell and thermal column. The same ratio was used^a for the epithermal activation.

**Evaluated assuming $1/v$ cross sections and using the value measured for thermal copper absorptions.

Infinitely dilute cross sections in the spectrum of the PCTR thermal column were determined using a THERMOS⁽⁸⁾ calculation for the whole PCTR. This calculation may be slightly in error since no leakage was assumed. For 0.010 inch thick copper a disadvantage factor of 1.011 was used.⁽¹¹⁾ The cross sections of the materials in the ²³³U particle were calculated using the fluxes calculated by THERMOS, the THERMOS library cross sections, and a routine CROSAV⁽¹²⁾ which derives effective cross sections from these data. Since only the fission activation was measured, a correction was also necessary for the difference in Σ_f/Σ_a between the thermal column and the lattice in order to obtain the total absorption rate. This correction was calculated by GRANIT and CROSAV and amounted to 0.12%. The thorium and 0.005 inch copper foils were assumed to have the same disadvantage factors in the lattice and in the thermal column. The effective cross sections for materials activated in the PCTR thermal column which were used in the analysis are presented in Table VI.

HTLTR EXPERIMENT

A. Test Lattice Description

The test lattice in the HTLTR, shown in Figure 5, differed from the PCTR lattice in several respects. The blocks containing ^{233}U are located in a 6 x 6 array and are surrounded on the radial perimeter by one layer of blocks from the first lattice⁽¹⁾ which contain ^{235}U . The center of the array, containing the four central cell blocks, extends through the reactor, i.e., is five blocks long. Surrounding this center area is a 4 x 4 array which is three blocks long. The outer two layers of the 8 x 8 HTGR block array are two blocks long. The blocks which are connected together to make up the central cell train, movable from the rear, and the front cell train which is used to insert test blocks into the void created when the rear train is moved 24 inches rearward, are also illustrated in Figure 5.

Surrounding the HTGR blocks are UO_2 shims, 5% enriched UO_2 drivers, gadolinium shims, control rods and fuel-poison columns. Two configurations were tried. In the first, the gadolinium shims were located interspersed with driver fuel in the ring adjacent to the HTGR blocks. The second loading is shown schematically in Figure 6. In this loading, the inner ring was filled with driver fuel and the gadolinium shims were moved one ring outward. Some graphite plugs were removed from the front and rear of the reactor in the vicinity of the HTGR blocks and additional graphite was placed near the control rods

FIGURE 5: ^{233}U HTGR CORE (CENTRAL REGION OF HTLTR CORE)

- X** 1 FIVE FOOT DRIVER + 2-10' END DRIVERS
- U** 4 NATURAL URANIUM SHIMS
- G** 2 GADOLINIUM TEMPERATURE SHIMS
- 1-10' END DRIVER AT FRONT + 1 AT REAR
- 2-10' END DRIVERS AT FRONT + 2 AT REAR

FIGURE 6: HTLTR FUEL LOADING DIAGRAM - ^{233}U - HTGR EXPERIMENT

to increase their worth. Also eight additional gadolinium shims were added to improve the overall temperature coefficient of reactivity of the reactor. This latter loading was used for the measurements at elevated temperatures.

B. Pre-experiment Calculations and Spectrum-matching Measurements.

To determine the reactor configuration likely to give a good flux match, calculations were carried out using the diffusion theory code 2-DB⁽¹³⁾ and a two group model of the HTLTR.⁽¹⁴⁾ The calculations of the two-group parameters for the HTGR lattice are described in Section VII. The first set of calculations used a configuration similar to the ²³⁵U lattice and predicted the neutron spectrum would be 1.4% too thermal. Measurement of the flux match using the cadmium ratio of .005 inch thick gold foils as a criterion indicated the spectrum to be mismatched by 5%. The adjoint flux was calculated to be mismatched by 2.3%. The 2-DB calculations also indicated that the loss in reactivity at 1000°C would be \$2.60 which was on the borderline of the amount that could be handled by adding reactivity via the fuel-poison columns. Moreover, a calculation at 1500°C predicted a \$.75 decrease in reactivity whereas an increase was expected based on past experience.

To improve the flux match and possibly the reactor temperature coefficient of reactivity, a second configuration was tried. This loading is described above and shown in Figure 6. Eight additional gadolinium shims were added to reduce the reactivity loss with heating. However, a loss of \$4.45 was predicted by the 2-DB calculation. It was decided to disregard this calculation since the two group model did not appear adequate to calculate meaningful temperature coefficients of reactivity. Subsequent experimental measurements showed this decision to be correct (see below).

The second loading had a calculated mismatch of 1.2% in the flux (still too thermal) but the adjoint mismatch was reduced to 0.2%. The calculated radial variation of the flux indicated, however, that the flux was matched and the 1.2% mismatch at the center presumably arises from the end cap perturbation. The measured flux mismatch for this loading was indicated to be less than 1%.

In addition to the flux match it is also desirable to have the flux flat axially to minimize streaming. A bare copper flux traverse, illustrated in Figure 7, showed the flux to be nearly flat with a slight flux tilt towards the rear of the reactor. This tilt was partially counteracted by moving the outer driver fuel one inch towards the front. The two peaks near the ends of the central cell are caused by the end cap perturbation. The flux decrease from the center of the

FIGURE 7: HTLTR AXIAL COPPER FLUX TRAVERSE

central cell to the center of the next cell (24-inches from the center) is only about 2%.

C. Room Temperature Measurements

At room temperature it is possible to make certain measurements that cannot easily be performed with the reactor heated. These reactivity measurements must then be used as a base point and their change with temperature calculated.

When measuring the cell reactivity worth, the cell is withdrawn from the rear using the heavy duty oscillator. In Figure 8, the case with the cell in place is illustrated by A, and with the cell withdrawn 24-inches to create the void by B. The numbers identify a group of four blocks attached together and C indicates the oscillator coupling.

The worth of the central cell could be measured by creating the configuration indicated in Figure 8C. In this case, the four central cell blocks are removed from the reactor. A modified cell withdrawn case is illustrated in Figure 8D where the four blocks (3) at the rear of the central cell are removed instead of the front blocks (1). Each of these configurations can be measured at room temperature.

FIGURE 8. REAR OSCILLATOR TRAIN CONFIGURATIONS

The required cell reactivity can then be expressed as

$$\begin{aligned}\Delta\rho^{\text{cell}} &= \rho_A - \rho_C = (\rho_A - \rho_B) + (\rho_B - \rho_D) + (\rho_D - \rho_C) \\ &= \Delta\rho_{\text{ext.}}^{\text{cell}} + \delta\rho_{\text{ext.}} + \delta\rho_{\text{subst.}}\end{aligned}\quad (1)$$

Two corrections to the measured $\Delta\rho_{\text{ext.}}^{\text{cell}}$ are defined in Equation (1).

The $\delta\rho_{\text{ext.}}$ arises from the extension of additional material outside of the reactor (blocks 3 in Figure 8B) which will act primarily as a reflector. The second correction, $\delta\rho_{\text{subst.}}$, arises from any difference in reactivity between blocks (1) and (2), and (2) and (3) as is compared in C and D. In the HTGR lattice, blocks (1) have couplings at only one end whereas (2) and (3) have couplings at both ends thereby creating an inherent difference in addition to any difference in fuel loading.

The values of the measured reactivities are given in Table VII. Both $\delta\rho_{\text{subst.}}$ and $\delta\rho_{\text{ext.}}$ are positive giving a $\Delta\rho_{\text{ext.}}$ which is a large correction to the measured cell worth. The sign of $\delta\rho_{\text{ext.}}$ is as expected but inspection of the loading data on the blocks used in the central cell train indicates that $\delta\rho_{\text{subst.}}$ should have a negative sign. The blocks at the rear of the train, (3) have a greater amount of both moderator and fuel (in spite of the smaller fuel volume due to the geometry difference mentioned above). The blocks at the center of the train (2), fall between (1) and (3) in density. The observed positive value of $\delta\rho_{\text{subst.}}$ therefore cannot be easily explained.

TABLE VII

Room Temperature Reactivity Measurements in HTLTR

	<u>Air Atmosphere</u>	
	<u>Measured Reactivity</u>	<u>Corrected for N₂</u>
$\Delta\rho^{\text{cell}}$	$8.107 \pm .025$	$7.217 \pm .025$
$\Delta\rho_{\text{ext.}}^{\text{cell}}$	$6.405 \pm .019$	---
$\Delta\rho_{\text{ext.}}$	$1.702 \pm .029$	---
$\delta\rho_{\text{ext.}}$	$.790 \pm .060$	---
$\delta\rho_{\text{subst.}}$	$.912 \pm .050$	---
$\Delta\rho_{\text{void}}^{\text{Cu}}$	$4.482 \pm .035$	---
$\Delta\rho_{\text{carrier}}^{\text{Cu}}$	$4.553 \pm .05$	---
$\Delta\rho_{\text{end caps}}$	$1.347 \pm .05$	$1.292 \pm .05$
$\Delta\rho_{\text{PCTR}}^{\text{cell}}$	$7.695 \pm .037$	$6.797 \pm .037$
<u>N₂ Atmosphere</u>		
$\Delta\rho^{\text{Cu}}$ (on carrier)	$4.443 \pm .05$	---
$\Delta\rho_{\text{(extension included)}}^{\text{cell}}$	$6.606 \pm .035$	$5.439 \pm .035$

Other reactivity measurements listed in Table VII provide other corrections to the measurements made at elevated temperatures. To insert the copper into the void it is necessary to use a graphite carrier. This perturbs the flux slightly and increases the copper worth. The measured ratio of the copper worth with the carrier to the worth without the carrier in the void is $1.016 \pm .014$.

The PCTR central cell is used as a reference for reactivity measurements and for the calculations. This cell has a slightly simpler geometry than the HTLTR central cell which is complicated by the coupling to the oscillator train. The ratio of the worth of the HTLTR cell to the PCTR cell (without the end cap worth subtracted) was measured in both reactors and the overall average is $1.067 \pm .005$.

D. Pressure and Temperature Coefficients of Reactivity

To compare reactivity values it is necessary to correct individual measurements to a standard condition of temperature and pressure. These corrections are made by measuring the pressure and temperature reactivity coefficients of the HTLTR at each operating temperature.

The pressure reactivity coefficient is measured by raising the pressure in the reactor enclosure and measuring the resulting change in reactivity. The pressure coefficient for an air atmosphere is approximately 78% of the pressure coefficient with a nitrogen atmosphere. The nitrogen pressure coefficient should vary approximately as

$$\left(\frac{\Delta\rho}{\Delta P}\right)_T = \left(\frac{\Delta\rho}{\Delta P}\right)_{20^\circ\text{C}} \frac{293}{T} \quad (18)$$

where T is the absolute temperature. It was found experimentally that the coefficient decreased slightly faster than indicated by this formula.

After the completion of the room temperature measurements in air, extra driver fuel was added, to compensate for the increased absorptions in a nitrogen atmosphere and to allow for the reactivity decrease expected from heating the HTLTR to 1000°C .

However, it was found that the reactivity increased with increasing temperature more rapidly than expected, and, after completion of the measurements at 150°C , it became necessary to remove fuel to remain within the operating restrictions on excess reactivity. The variation of the excess reactivity of

the HTLTR as a function of temperature after this fuel removal is shown in Figure 9. The point at 25° is an estimate based on the amount of fuel removed. At temperatures of 750°C and 1000°C, reactivity was added via the fuel-poison columns to obtain an excess reactivity adequate to permit measurements.

The temperature coefficient may be determined at each operating temperature from the slope of the curve in Figure 9. These coefficients were also determined at each temperature level by changing the reactor temperature by about 10°C and measuring the reactivity change. The measurements by the two methods are compared in Table VIII. Good agreement is obtained at 500°C and 750°C where the slope measurements are most accurate. Reasonable agreement is obtained at the other temperatures.

TABLE VIII

HTLTR Temperature Coefficient of Reactivity

<u>Temperature, °C</u>	<u>Measured Temperature Coefficient, $\phi/^{\circ}\text{C}$</u>	<u>Temperature Coefficient from Slope in Figure 9, $\phi/^{\circ}\text{C}$</u>
20	+0.81	+0.88
150	+0.29	+0.32
300	+0.103	+0.082
500	-0.118	-0.120
750	-0.28	-0.29
1000	-0.51	-0.43

FIGURE 9: HTLTR EXCESS REACTIVITY

E. Reactivity Measurements vs. Temperature

At each temperature, measurements were made of the reactivity worth of the central cell, copper, copper carrier, single fuel block, ^{235}U block and the poison blocks. Except for the central cell, these measurements were made by inserting the sample from outside the reactor enclosure into the void using the light duty oscillator. The results of these reactivity measurements, corrected for the N_2 in the void, are summarized in Table IX. The derivation of the nitrogen correction is given in Appendix B.

The reactivity measurements at room temperature are straightforward. Reactivity measurements can be made in rapid succession and thus uncontrollable changes in the reactor between runs are small. In addition, the samples inserted in the void are at approximately the same temperature so no transient temperature effect is created.

When the reactor temperature is above room temperature, insertion of a cold sample into the reactor creates a transient condition during the time the sample heats to the reactor temperature and the reactor regains temperature equilibrium. Transients are also created when the vertical safety rods are inserted or when heater power is changed. These effects greatly complicate the accurate measurement of reactivities.

TABLE IX

Reactivity Worths (in cents) as a Function of Temperature (N_2 Corrected)

	20°	150°	300°	500°	750°	1000°
Central Cell	5.439±.035	4.264±.087	3.253±.040	2.549±.043	1.953±.058	1.943±.067
Central Cell Corrected for Extension	7.125±.022	5.966±.092	4.955±.049	4.251±.052	3.655±.065	3.645±.073
Copper (209.2 gm)	- 4.55 ±.05	- 4.44 ±.09	- 4.52 ±.10	- 4.34 ±.07	- 4.09 ±.06	- 4.15 ±.09
Graphite Carrier	1.25 ±.05	1.30 ±.09	1.28 ±.10	1.31 ±.08	1.24 ±.06	1.08 ±.09
^{233}U Block	1.82 ±.05	1.22 ±.15	1.32 ±.06	1.18 ±.06	.98 ±.06	.76 ±.10
^{235}U Block	3.92 ±.06	4.03 ±.15	3.20 ±.06	2.78 ±.06	2.36 ±.06	2.20 ±.10
Europium Block	-10.52 ±.08	- 9.95 ±.20	- 8.72 ±.06	- 9.02 ±.15	-10.73 ±.08	-12.81 ±.15
Samarium Block	-30.85 ±.08	-32.25 ±.15	-32.58 ±.08	-31.52 ±.15	-26.45 ±.08	-23.57 ±.15
Hafnium Block	-36.12 ±.08	-34.59 ±.15	-35.11 ±.12	-35.80 ±.12	-34.64 ±.08	-36.82 ±.15
Rhodium Block	-28.75 ±.08	-27.85 ±.15	-28.17 ±.12	-29.19 ±.12	-28.82 ±.08	-31.34 ±.15
Gadolinium Block	-43.12 ±.06	-39.76 ±.15	-36.31 ±.12	-32.50 ±.12	-25.25 ±.08	-21.60 ±.15

To allow the sample to reach temperature and to eliminate the transient effect, a series of reactivity runs is made encompassing a period of several hours. Thus, by following the reactivity changes, it is possible to extrapolate to the correct reactivity that would be measured at complete temperature equilibrium. However, because one reactivity measurement by this technique is now extended to several hours, other drifts in the reactor will lead to uncertainties in the reactivity measurement which may be much larger than those observed at room temperature.

Temperature measurements in the HTLTR are made using resistance temperature detectors (RTDs) and thermocouples. The former are accurate to about $.01^{\circ}\text{C}$, but, only one RTD was available to be read and therefore the temperature at only one point in the reactor is represented. If this temperature can be taken as typical, then temperature corrections can be evaluated. The thermocouples are much less accurate ($\sim 1^{\circ}\text{C}$) and at the time of this experiment were referred to the ambient control room temperature which was observed to vary. Therefore, the thermocouples are inadequate for accurate temperature reactivity corrections. However, they are distributed throughout the reactor, enabling a spatial evaluation of temperature and they are used for heater control. The errors in thermocouple reading, therefore, put a limit on the reactor temperature stability.

Each temperature level presents its own peculiarities in the data analysis. At 150°C, heat transfer in the reactor occurs slowly. For example, during the runs at this temperature, the heat program shut off, causing a major change in reactivity and a transient that lasted for a period of hours. It was particularly difficult to correlate temperature changes with reactivity measurements, since the different parts of the reactor were not sufficiently well coupled thermally that temperature corrections could be made in any simple manner. In addition, heater control was particularly difficult at 150°C, since heater power is controlled by a difference signal which is small because heat losses are small. Changes in the control room temperature influenced the thermocouple reference junction temperature and could cause heater power changes that are a significant fraction of the power required to maintain a constant temperature. Attempts were made to keep the heater power constant under manual control. However, this technique also was not dependable because of the low power and drifts in the control instrumentation. Data were analyzed by averaging and attempts were made to keep temperature perturbations as small as possible.

At 300°C heat transfer occurs more rapidly and the effect of the inserted cold sample becomes more important. Runs were made with the heater power held constant and the reactivity data was analyzed by averaging and in some cases by extrapolation.

At 500°C, the heater power was still held constant but it was found that each cold sample lowered the overall reactor temperature enough to create a trend throughout the experiment. Data from each reactivity series were fit with a decaying exponential function using the least squares fitting program LEARN.⁽¹⁵⁾ Two methods were used. In one method, the reactivity data, uncorrected for temperature changes, were fit and an extrapolated equilibrium temperature was obtained. The fitted equilibrium reactivity value was then corrected for the difference between the extrapolated temperature and the reference temperature. In the second method the reactivity data were first corrected for temperature differences and the temperature-corrected data were fit using LEARN. Reasonable agreement between the two methods was usually obtained. On some runs, reactor drifts were larger than the reactivity transient associated with the sample and in these cases it was necessary to estimate the extrapolated reactivity value. The quoted errors generally reflect these uncertainties.

At 750°C, the heat was put under automatic control. The data were handled as in the 500°C runs and good results were obtained. The response of the instrumentation to temperature changes was reasonably good and the RTD temperature seemed to give temperature corrections that were accurate.

The RTD was not operable at 1000°C, and thus no precise temperature measurements were available. Although the top heater control was erratic, the overall reactor heater control was adequate so overall temperature perturbations were small. The reactivity changes due to differences in temperature were estimated using average thermocouple temperatures. Since the HTLTR temperature coefficient of reactivity is large in magnitude at 1000°C, the errors in the data are somewhat larger. The reactivity transient caused by heating the cold sample are largest at 1000°C, but heat transfer is good and so the time constants are short, thus leading to a more accurate least squares analysis.

The reactivities obtained by the above analysis, and corrected for nitrogen in the void, are presented in Table IX together with the estimated standard errors. The room temperature values which were measured in air have been corrected to a nitrogen atmosphere.

The ratio of the sample reactivity worths to the copper worth per gram modified by $1 + a$ (see Appendix A) to include only the thermal worth is presented in Table X. The values are obtained directly from Table IX except at 300°C, at which temperature the measured copper reactivity is indicated by the data to be high. Accordingly the values presented in Table X were for the copper reactivity at 300°C lowered by 2.4%, to achieve consistency among all the data (cf. Figures 10 through 15).

TABLE X

Reactivities Normalized to Thermal Absorber*

	20°	150°	300°	500°	750°	1000°
Copper $-\Delta\rho/(1+a)M^{\text{Cu}}$ ¢/gm	.01914±.00021	.01877±.00038	.01865±.00041	.01831±.00030	.01726±.00025	.01748±.00037
Central Cell	- 367.8± 2.9	- 317.8± 8.1	- 265.7± 6.4	- 232.2± 4.7	- 211.8± 4.9	- 208.5± 6.0
Graphite Carrier	- 65.2± 1.8	- 69.4± 5.0	- 68.8± 5.6	- 71.7± 4.5	- 71.9± 3.6	- 62.0± 5.2
Single Block	- 94.8± 2.8	- 65.0± 8.1	- 71.0± 3.2	- 64.5± 3.4	- 56.7± 3.6	- 43.2± 5.7
²³⁵ U Block	- 204.0± 3.9	- 214.8± 9.1	- 171.6± 5.0	- 150.0± 4.1	- 136.9± 4.0	- 125.9± 5.8
Europium Block	547. ± 6	530. ±13	465. ±10	484. ±11	622. ±10	733. ±18
53 Samarium Block	1603. ±17	1723. ±40	1736. ±39	1690. ±29	1532. ±24	1348. ±30
Hafnium Block	1877. ±20	1843. ±42	1871. ±42	1920. ±33	2007. ±30	2106. ±46
Rhodium Block	1494. ±16	1484. ±34	1501. ±34	1565. ±27	1670. ±26	1793. ±40
Gadolinium Block	2241. ±24	2118. ±48	1934. ±43	1743. ±30	1463. ±23	1236. ±28

*Except for the copper worth, the values in this table are reactivities of samples divided by the reactivity due to thermal absorptions in one gram of copper.

VI. DATA ANALYSIS AND RESULTS

A. Corrections to Reactivity Data

In order to obtain the correct $\Delta\rho$ cell required in equation 11, at each temperature, corrections must be made for the difference between the measured situation and the ideal situation of a simple cell in the void. These corrections include corrections for the extension effect, differences between the PCTR and HTLTR central cells, and perturbations caused by the end caps and the graphite copper carrier.

The measurement of the room temperature value for the reactivity worth due to the extension effect is described in Section V. Attempts were made to calculate the temperature dependence of this effect using 2 DB⁽¹³⁾ and the perturbation theory code PERT-V.⁽¹⁶⁾ These codes predicted a slight increase in the worth of the extension with temperature, but the validity of this result is very uncertain due to the inability of the code to predict accurate temperature coefficients of reactivity and accurate copper worths in the void. In view of this inadequacy at the present level of sophistication of the calculational model, it was decided to assume the extension effect to be constant. Additional evidence for this assumption is presented in Figure 10, where the single block worth data,

FIGURE 10. COMPARISON OF CENTRAL CELL AND SINGLE CELL WORTH

which requires no extension correction, but has a percentage experimental error about 4 times as large, is compared to the central cell worth corrected with the constant extension effect correction. The two have been normalized at room temperature. The errors in the central cell measurement have not been plotted.

The cell reactivity must also be corrected for the end cap worth to obtain a k_{∞} for an infinite length cell. This worth was measured at room temperature with graphite pieces in the void and it is assumed that the worth is unchanged when the central cell is in place. Since the measured graphite carrier worth in the void was nearly constant (see Table IX) it was assumed that the end cap correction could be taken to be constant.

To normalize the PCTR central cell, which was used as the standard, the HTLTR central cell worth after correction for the two effects above, was divided by the average ratio of the HTLTR cell worth to PCTR cell worth. This ratio was $1.040 \pm .010$. The final corrected $\Delta\rho^{\text{cell}}$ values are presented in Table XI.

The copper reactivity worth was measured using a graphite carrier which increased the copper worth $1.016 \pm .014$. The copper worth was also divided by $(1 + a)$ to normalize to the thermal copper absorptions only. The calculation of the epithermal correction a versus temperature is described in Appendix A. The copper reactivity worths with the above corrections are also presented in Table XI.

B. Corrections to the Measured Cell Absorptions

The cell absorptions were evaluated experimentally only at room temperature. Therefore, the change in total cell absorptions relative to the absorptions in a $1/v$ absorber at the cell surface was evaluated using GRANIT⁽¹⁰⁾ a modification of THERMOS.⁽¹⁷⁾ The correction factors for each temperature are given in Table XI.

Since the cell absorptions are then normalized to a $1/v$ absorber at the cell surface, a correction is necessary for the change in the difference between the number of copper absorptions at the cell surface and in the void. The PCTR measurements indicate the copper to absorb about 0.4% fewer neutrons in the void at room temperature whereas a 2 DB calculation predicted 1.5% more in the void. Since 2 DB cannot reproduce the effect and since the effect is small (and its change with temperature even smaller) this correction was neglected.

The cell and copper absorptions for each temperature are also presented in Table XI.

C. Mismatch Corrections

As stated above, the spectrum mismatch at the center of the central cell was very small. However, due to the presence of the end caps, the spectrum near the ends of the cell was quite different from the equilibrium spectrum for the cell in the absence of end caps. Using the one dimensional transport code DTF-IV⁽⁹⁾ with two energy groups and slab geometry with a homogeneous fuel region, average values over the cell of 1.7371 for ϕ_1^+/ϕ_2^+ and .8051 for ϕ_1^+/ϕ_2^+ were calculated. The latter was assumed to be the same for the surface of the void. The equilibrium values for the flux and adjoint ratios are 1.8223 and .8013, respectively. Recalling equation (4) where ϕ is defined as ϕ_1/ϕ_2 and $\Delta\phi$ is the equilibrium ratio minus the cell ratio, $\Delta\phi/\phi$ is calculated to be -.0468 and $\Delta\phi^+/\phi^+$ is +.0047, assuming the flux and adjoints are closely matched radially and axially using the experimental criterion. It was assumed that the flux mismatch due to the end caps did not change with temperature. A calculation with 2-DB indicated that if the spectrum is matched at room temperature, it will be closely matched at 1000°C. Therefore $\Delta\phi/\phi$ and $\Delta\phi^+/\phi^+$ were assumed to be constant with temperature.

TABLE XI

Evaluation of Experimental k_{∞}

	20°	150°	300°	500°	750°	1000°
$\Delta\rho^{\text{cell}}$ corrected	5.609±.078	4.494±.114	3.522±.078	2.845±.078	2.272±.085	2.262±.091
$(\Delta\rho^{\text{Cu}}/M^{\text{Cu}}) \phi/\text{gm}$	.02130±.00018	.02091±.00043	.02078±.00048	.02041±.00033	.01926±.00029	.01952±.00042
1 + a	1.1131	1.1138	1.1142	1.1149	1.1158	1.1170
$\Delta\rho^{\text{cell}}(1+a)/(\Delta\rho^{\text{Cu}}/M^{\text{Cu}})$	293.1±4.7	239.4±7.8	188.9±6.1	155.5±4.9	131.6±5.3	129.4±5.9
Relative Thermal Absorptions in Cell	1.0	1.0001	1.0011	1.0051	1.0110	1.0185
Cell Absorptions/copper absorptions per gram	4008±75	4008±75	4012±75	4028±76	4052±76	4082±76
A (no mismatch)	.0731±.0018	.0597±.0022	.0471±.0018	.0386±.0014	.0325±.0014	.0317±.0016
A (with mismatch)	.0729±.0018	.0595±.0022	.0469±.0018	.0384±.0014	.0323±.0014	.0315±.0016
b_1 (Equation 15)	.7840	.7788	.7722	.7650	.7563	.7485
b_2 (Equation 16)	.285	.237	.206	.174	.140	.113
$b_1 A$	.0572±.0014	.0463±.0017	.0362±.0014	.0294±.0011	.0244±.0011	.0236±.0012
$b_2 A^2$	.0015	.0008	.0005	.0003	.0001	.0001
k_{∞} (Equation 14)	1.0587±.0014	1.0471±.0017	1.0367±.0014	1.0297±.0011	1.0245±.0011	1.0237±.0012

D. Evaluation of Experimental k_{∞}

The evaluation of k_{∞} from the experimental data using Equation 14 is outlined in Table XI. The first two rows present the reactivity data corrected as described above. The epithermal correction for copper, a , is calculated as described in Appendix A. The room temperature cell absorption relative to copper absorption per gram follows directly from Table VI. The relative absorption at the elevated temperatures is obtained by applying the calculated correction factor. The quantity A is evaluated from the experimental data using Equation 11 and b_1 and b_2 are calculated correction factors defined in Equations 15 and 16. The parameters used to obtain b_1 and b_2 were calculated using the computer codes GRANIT⁽¹⁰⁾ and EGGNIT.⁽⁷⁾ This calculation is described further in section VII. Equation (14) is then used to evaluate k_{∞} at each temperature.

The errors in k_{∞} are assigned on the basis of the experimental errors which have been combined statistically to obtain the standard error in the final result. Systematic errors arising from various assumptions made above are more difficult to evaluate and have not been included. These errors are all estimated to be small.

When differences in k_{∞} are calculated, the error due to the uncertainty in the cell absorption rate is not as significant since the absorption at elevated temperatures is derived from the room temperature value. Evaluating the difference in k_{∞} between 20°C and 1000°C results in $.0350 \pm .0015$.

E. Evaluation of $\hat{\eta}^{233}$

Using the definition of k_{∞} in Equation 1, and substituting the absorptions and fissions for each isotope results in the expression

$$\Sigma_a^{233} = \frac{\nu \Sigma_f^{233}}{k_{\infty}} + \left(\frac{\nu \Sigma_f^{232}}{k_{\infty}} - 1 \right) \Sigma_f^{232} + \left(\frac{\nu \Sigma_f^{235}}{k_{\infty}} - 1 \right) \Sigma_f^{235} \quad (19)$$

$$- \Sigma_c^{232} - \Sigma_c^{235} - \Sigma_a^{\text{cell}}$$

where the small amount of ^{235}U has been included and Σ_a^{cell} includes all cell absorptions except in ^{232}Th , ^{233}U , and ^{235}U . This equation may be written.

$$\hat{\eta}^{233} = \frac{1}{\frac{1}{k_{\infty}} + \frac{1}{(\nu \Sigma_f)^{233}} \left(\frac{\nu \Sigma_f^{232}}{k_{\infty}} - 1 \right) \Sigma_f^{232} + \left(\frac{\nu \Sigma_f^{235}}{k_{\infty}} - 1 \right) \Sigma_f^{235} - \Sigma_c^{232} - \Sigma_c^{235} - \Sigma_a^{\text{cell}}} \quad (20)$$

The fluxes have been omitted from this expression but, for example, Σ_c^{232} stands for the total captures in thorium at all energies.

Evaluation of $\hat{\eta}^{233}$ from equation (20) provides a separate check on the consistency of the data from Table VI and the k_∞ evaluation. The value of $\hat{\eta}^{233}$ obtained is $2.46 \pm .11$. This value falls above the accepted 2200 m/sec value⁽¹⁸⁾ of $2.292 \pm .006$ and the value calculated by GRANIT of 2.279. The errors in the foil activation measurements and the uncertainty in the ^{233}U loading preclude obtaining a more accurate value of η by this method.

F. Poison Blocks

The normalized reactivity data for the poison blocks, which is presented in Table X, is plotted in Figures 11 through 15 vs. the square root of the absolute temperature. The data has been normalized to room temperature in these plots and is compared with the Westcott g factor⁽¹⁹⁾ (the ratio of the cross section in a Maxwellian spectrum to that of a $1/v$ absorber) similarly normalized. Qualitative similarity between the two curves is noted. The Westcott curve does not take into account the hardening of the thermal flux due to absorption, which would bring the curves closer together in each case. In addition, the Westcott curve does not take into account the epithermal absorptions which are relatively small for these poison materials or any effect of changes in the adjoint flux.

FIGURE 11. RELATIVE WORTH OF SAMARIUM

FIGURE 12: RELATIVE WORTH OF EUROPIUM

FIGURE 13: RELATIVE WORTH OF HAFNIUM

FIGURE 14: RELATIVE WORTH OF RHODIUM

FIGURE 15: RELATIVE WORTH OF GADOLINIUM

G. Worth of ^{235}U Block

For comparison with the initial HTGR experiment, the reactivity of a central cell block from the ^{235}U lattice was measured at each temperature in the ^{233}U lattice. A comparison of these worths with those measured in the previous lattice is presented in Figure 16. The relative worths in this figure are normalized to the copper worth, adjusted to thermal absorptions, at each temperature. As expected, in the more thermal spectrum the ^{235}U block has a higher reactivity worth and a smaller drop in reactivity with increasing temperature.

FIGURE 16: RELATIVE WORTH OF ^{235}U FUEL BLOCK

VII. THEORETICAL CALCULATION OF k_{∞} AND COMPARISON WITH EXPERIMENT

Using the definition of k_{∞} given in Equation 1, and eliminating the fluxes using Equation 3, it is found that:

$$k_{\infty} = \frac{\eta_2 f_2 p + \eta_1 f_1 (1-p) + \eta_1 f_1 (1-p) L^2 B^2}{1 + (1-p) L^2 B^2} \quad (21)$$

The buckling may be evaluated to first order by

$$B^2 = \frac{\eta_1 f_1 (1-p) + \eta_2 f_2 p - 1}{\tau + L^2 [1 - \eta_1 f_1 (1-p)]} \quad (22)$$

The values of k_{∞} and B^2 evaluated from these equations, together with the parameters needed in the evaluation are presented in Table XII.

The computer codes EGGNIT⁽⁷⁾ and GRANIT⁽¹⁰⁾ were used to calculate the parameters on the right hand side of the above equations. These parameters were also used in the calculation of the correction factors b_1 and b_2 that are used in the evaluation of the experimental k_{∞} .

EGGNIT is a modification of GAM⁽²¹⁾ that uses the Nordheim integration technique⁽²²⁾ and takes into account particle effects in the fuel mixture. EGGNIT was used to calculate the epithermal parameters for neutron energies above 0.683 ev. The correct buckling was supplied as input in order to use the correct leakage in obtaining the cross sections for one broad group.

TABLE XII

Theoretical Parameters and k_{∞}

	20°	150°	300°	500°	750°	1000°
τ (Equation 5) cm^2	354.27	351.84	350.04	347.67	345.31	343.23
$\eta_1 f_1$ (Equation 7)	.59498	.56994	.54867	.52773	.50939	.49629
p (Equation 8)	.67702	.66674	.65754	.64830	.63915	.63178
L^2 (Equation 6) cm^2	233.55	248.54	272.17	298.56	331.14	361.06
$\eta_2 f_2$	1.2732	1.2747	1.2772	1.2826	1.2910	1.2997
$\eta_1 f_1 (1-p)$	.19217	.18994	.18790	.18560	.18381	.18274
$\eta_2 f_2 p$	.86198	.84989	.83981	.83151	.82514	.82112
B^2 (Equation 22) cm^{-2}	.997x10 ⁻⁴	.720x10 ⁻⁴	.485x10 ⁻⁴	.290x10 ⁻⁴	.147x10 ⁻⁴	.060x10 ⁻⁴
$L^2 B^2$	.0233	.0179	.0132	.0086	.0048	.0022
k_{∞} (Equation 21)	1.0507	1.0370	1.0256	1.0156	1.0081	1.0034

The thermal region was analyzed using GRANIT, a modification of THERMOS,⁽¹⁷⁾ that also is able to compute the effects of particle size. Thirty energy groups were used in the range 0 to 0.683 ev. The edge of the cylindricized cell was treated as having a white boundary.

A comparison of the theoretical and experimental values of k_{∞} plotted versus the square root of the absolute temperature is presented in Figure 17. It may be noted that the experimental curve lies above the predicted k_{∞} at all temperatures and also exhibits much less change with temperature, particularly at the higher temperatures.

At room temperature, the experimental value of k_{∞} is 0.0050 above the calculated value. This difference is larger than the error in the experimental value. The uncertainty in the exact loading of the fuel blocks could account for the difference, however. The one percent uncertainty in the amount of ^{233}U leads to an uncertainty in k_{∞} of 0.0040. Other errors that might contribute include differences between the particle sizes used in the central cell blocks and the measured ThO_2 sample or the quoted UO_2 - ThO_2 sphere size, differences between the actual loading and an ideal distribution of fuel mixture, and the difference between the blocks with end caps and an infinite lattice (only approximately taken into account).

FIGURE 17. COMPARISON OF EXPERIMENTAL AND THEORETICAL k_{∞}

In addition, errors in the cross sections used in the calculations can have some effect. Thus, the 0.0050 difference between the calculated and measured room temperature k_{∞} can be regarded as a reasonable error.

The change in k_{∞} from 20°C to 1000°C was calculated to be -0.0473 in comparison with the experimental value of -0.0350 $\pm$.0015. Thus there is a significant difference between the predicted and measured values. This difference cannot be accounted for by the uncertainties in fuel loading mentioned above. In fact, an increase of one-percent in the ^{233}U concentration was calculated to cause the change in k_{∞} to be larger by 0.0005. The other possible systematic uncertainties would be expected to have similar small effects.

In the first HTGR experiment, using ^{235}U , the experimental decrease in k_{∞} of 0.073 was larger than the predicted change of 0.064.⁽²⁰⁾ Since the differences are opposite in sign, it is unlikely that the difference between experiment and theory can be attributed to a systematic error in either experiment or calculation. The third HTGR experiment, which will use a ^{233}U -Th loading with the carbon to thorium atom ratio raised to 300, will provide additional evidence on this matter.

VIII. Conclusions

The $^{233}\text{UO}_2\text{-ThO}_2$ experiment described in this report is the second in a series of HTGR experiments which provide data of direct use in the reactor design calculations of advanced high-temperature gas-cooled reactors. The experiments cover a variety of loadings spanning the range used in reactor design. These experiments will complement each other by providing evidence on the accuracy of the HTLTR methods and indicating effects that cause inaccuracies, and by pinpointing deficiencies in the theoretical calculations.

In the present experiment a significant difference between experimental and theoretical values of the change in k_∞ with temperature was observed. This difference cannot be immediately explained by experimental errors or by errors in the analysis. The analysis of additional experiments in the HTLTR-HTGR series should shed some light on the source(s) of this discrepancy, and may help to identify any areas in the analysis methods that need further study and improvement.

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Appendix A

Analysis of Epithermal Copper Absorptions

Since copper is not a pure thermal absorber

$$\chi \Delta \rho^{Cu} = \sum_{i=1}^n \phi_i \frac{\Sigma_i^{Cu}}{\Sigma_{th}^{Cu}} \phi_i V^{Cu} \quad (A1)$$

which may be written

$$\chi \Delta \rho^{Cu} = (\Sigma \phi V)_{th}^{Cu} \left\{ 1 + \sum_{i=1}^{n-1} \frac{\phi_i \Sigma_i^{Cu}}{\phi_{th} \Sigma_{th}^{Cu}} \frac{\phi_i}{\phi_{th}} \right\} \quad (A2)$$

or

$$\chi \Delta \rho^{Cu} = (\Sigma \phi V)_{th}^{Cu} (1 + a) \quad (A3)$$

Where a now represents the deviation of copper from a pure thermal absorber. In the above multigroup notation,

$$a = \sum_{i=1}^{n-1} \frac{\phi_i \Sigma_i^{Cu}}{\phi_{th} \Sigma_{th}^{Cu}} \frac{\phi_i}{\phi_{th}} \quad (A4)$$

In the past, this has been evaluated using an extended two group method in which the epithermal absorptions are divided into a resonance part and a $1/v$ part. The latter part is estimated to have the same worth as the thermal neutrons. If RI_{ex}^{Cu} is the part of the copper resonance integral due to resonances and RI_{epi}^{Cu} is the total resonance integral above the cadmium cutoff (.683 ev), then

$$a = \frac{RI_{epi\ Cd}^{Cu} - RI_{ex}^{Cu}}{RI_{epi\ Cd}^{Cu}} \frac{\Sigma_1 \phi_1}{\Sigma_{th} \phi_{th}} + \frac{\phi_1^+}{\phi_{th}^+} \frac{RI_{ex}^{Cu}}{RI_{epi\ Cd}^{Cu}} \frac{\Sigma_1 \phi_1}{\Sigma_{th} \phi_{th}} \quad (A5)$$

or since the copper cadmium ratio (CdR) is given by

$$CdR = \frac{\Sigma_{th} \phi_{th} + \Sigma_1 \phi_1}{\Sigma_1 \phi_1}$$

the experimental value of a is then,

$$a = \frac{1}{CdR-1} \left[1 - \left(1 - \frac{\phi_1^+}{\phi_{th}^+} \right) \frac{RI_{ex}^{Cu}}{RI_{epi-cd}^{Cu}} \right] \quad (A7)$$

Using values given by Bennett⁽¹¹⁾ of 13705b for RI_{ex}^{Cu} and 2.8805b for $RI_{epi\ Cd}^{Cu}$, the calculated value using EGGNIT - GRANIT - HFN of .8013 for ϕ_1^+/ϕ_2^+ , and the measured .010-inch copper cadmium ratio (corrected by 3.3% for the calculated cadmium flux depression) of 8.942, the value of a is calculated to be 0.1140.

However, since a is temperature dependent, an evaluation was made using EGGNIT - GRANIT - HFN results. It was decided to use six groups (although not necessary for this analysis) and the group boundaries are shown in Table XIII. For copper the resolved resonance contributions are contained in group 2, and the cross section in the lower energy groups is $1/v$. The main $1/v$ contribution comes from groups 4 and 5 which have a neutron worth close to thermal, thus confirming the validity of the above model. The thermal copper cross section was assumed to be $1/v$ (as given by GRANIT) with an average flux depression at room temperature in the copper of 1.10%. The flux depression was taken proportional to the $1/v$ cross section at higher temperatures.

TABLE XIII

Six Group Energy Boundaries

Group	Lower Energy	Upper Energy	Lethargy Units in Group
1	11.7×10^3 ev	10^7 ev	6.75
2	167	11.7×10^3	4.25
3	17.6	167	2.25
4	2.38	17.6	2.00
5	0.683	2.38	1.25
6 (Thermal)	0.0	.683	---

The epithermal cross sections were calculated using a modification of EGGNIT which calculated the resonance self-shielding for the .010-inch copper foil without including the copper in the unit cell. It was assumed that the epithermal flux depression in the copper, except in the resonances, can be neglected and that the fundamental mode fluxes and adjoints are the ones existing in the void.

The calculation at room temperature gave 7.992 for the ratio of thermal to epithermal absorptions (CdR-1) as compared to the experimental value of 7.942 (about a 0.6% difference). Accordingly the values at each temperature were normalized to give the correct ratio to the experimental room temperature cadmium ratio. Thus

$$a = \frac{1}{\text{CdR}-1} \frac{(\sigma\phi)_{\text{th}}^{20}}{\sum_{i=1}^5 (\sigma\phi)_i^{20}} \sum_{i=1}^5 \frac{\phi_i \sigma_i^{+ \text{Cu}}}{\phi_{\text{th}} \sigma_{\text{th}}^{+ \text{Cu}}} \frac{\phi_i}{\phi_{\text{th}}} \quad (\text{A8})$$

where $(\sigma\phi)^{20}$ indicates the cross section times flux at 20°C and the CdR is only evaluated at room temperature. The value of "a" from Equation 8 at room temperature is 0.1131 which agrees quite well with the approximate model. The values of "a" calculated at each temperature are given in Table XIV. It is seen that the temperature effect from this source is small.

TABLE XIV

Epithermal Copper Correction Term "a"

<u>Température</u>	<u>"a"</u>
20°	.1131
150°	.1138
300°	.1142
500°	.1149
750°	.1158
1000°	.1170

Appendix B

The Nitrogen Correction

In the HTLTR or PCTR, when the central cell is removed from the reactor, a cavity is left containing air or nitrogen. This gas will absorb and scatter neutrons and thus a correction must be calculated to correct the measured reactivity change to that for the case of a true void.

The reactivity of the nitrogen can be written as:

$$\Delta\rho^{N_2} = \frac{-V}{\chi} \sum_i \phi_i^+ \Sigma_i^a \phi_i + \frac{V}{\chi_{ij}} (\phi_i^+ - \phi_j^+) \sum_{j \rightarrow i} \phi_j \quad (B1)$$

or

$$\Delta\rho^{N_2} = \Delta\rho_a^{N_2} + \Delta\rho_s^{N_2} \quad (B2)$$

where $\Delta\rho_a$ is the absorption reactivity effect and $\Delta\rho_s$ is the scattering effect. The former is by far the most important. Since N_2 is mainly a $1/v$ absorber, this term may be obtained from the measured copper reactivity. However, since both N_2 and copper deviate from $1/v$, a correction to the copper reactivity is necessary.

Using Equation (A1) for the copper reactivity,

$$\frac{\Delta \rho_a^{N_2}}{\Delta \rho^{Cu}} = \frac{(\sum \phi V)_{th}^{N_2} \sum_i \frac{\phi_i^+ \sigma_i^{N_2}}{\phi_{th}^+ \sigma_{th}^{N_2}} \frac{\phi_i}{\phi_{th}}}{(\sum \phi V)_{th}^{Cu} \sum_i \frac{\phi_i^+ \sigma_i^{Cu}}{\phi_{th}^+ \sigma_{th}^{Cu}} \frac{\phi_i}{\phi_{th}}} \quad (B3)$$

or using the same six group model defined in Appendix A,

$$\Delta \rho_a^{N_2} = \Delta \rho^{Cu} \frac{(\sum \phi V)_{th}^{N_2}}{(\sum \phi V)_{th}^{Cu}} \frac{1 + z \sum_{i=1}^5 \frac{\phi_i^+ \sigma_i^N}{\phi_{th}^+ \sigma_{th}^N} \frac{\phi_i}{\phi_{th}}}{1 + z \sum_{i=1}^5 \frac{\phi_i^+ \sigma_i^{Cu}}{\phi_{th}^+ \sigma_{th}^{Cu}} \frac{\phi_i}{\phi_{th}}} \quad (B4)$$

where z is the ratio of the experimental room temperature cadmium ratio-1 to the calculated value and is inserted to normalize the epithermal flux to the experimental measurement.

The nitrogen reactivity may now be written as

$$\Delta \rho^{N_2} = \Delta \rho^{Cu} \frac{(\sum \phi V)_{th}^{N_2}}{(\sum \phi V)_{th}^{Cu}} (1-c) \quad (B5)$$

where c is the correction for the difference between the copper and nitrogen epithermal absorption. The value of c is defined by:

$$c = \frac{z \sum_{i=1}^5 \frac{\phi_i^+ \sigma_i^{Cu}}{\phi_{th}^+ \sigma_{th}^{Cu}} \frac{\phi_i}{\phi_{th}}}{1 + a} \quad (B6)$$

where a is the copper epithermal term calculated in Appendix A.

The epithermal N_2 absorption was calculated by EGGNIT for the nitrogen in the cell and this was assumed adequate for the void because of the small resonance absorption in nitrogen. The values of c for each temperature are given in Table XV.

TABLE XV

CORRECTION TERMS FOR NITROGEN CORRECTION

<u>Temperature</u>	<u>Epithermal Correction Term</u>	<u>Thermal Disadvantage Factor</u>
	C	D
20 °	.0397	1.0110
150	.0406	1.0103
300	.0409	1.0094
500	.0416	1.0085
750	.0425	1.0076
1000	.0433	1.0069

The above method for determining c may be compared to the two energy group method used previously. Using RI_{ex}^{Cu} for the part of the copper resonance integral due to resonances and $RI_{epi Cd}^{Cu}$ for the total resonance integral above the cadmium cut off (0.683 ev) then

$$\begin{aligned} \chi \Delta \rho^{Cu} = & \phi_2^+ \Sigma_2 \phi_2 + \phi_2^+ \frac{RI_{epi Cd}^{Cu} - RI_{ex}^{Cu}}{RI_{epi Cd}^{Cu}} \Sigma_1 \phi_1 \quad (B7) \\ & + \phi_1^+ \frac{RI_{ex}^{Cu}}{RI_{epi Cd}^{Cu}} \Sigma_1 \phi_1 \end{aligned}$$

where all neutrons absorbed in the $1/v$ region above the cadmium cut off are taken to have the same worth as thermal neutrons, ϕ_2^+ .

If $\Delta \rho^{Cu'}$ is the part of the copper reactivity due to $1/v$ absorptions, then the part of the reactivity not to be included is given by

$$\chi(\Delta \rho^{Cu} - \Delta \rho^{Cu'}) = \phi_1^+ \frac{RI_{ex}^{Cu}}{RI_{epi Cd}^{Cu}} \Sigma_1 \phi_1 \quad (B8)$$

Using the copper cadmium ratio (measured),

$$CdR^{Cu} = 1 + \frac{\Sigma_2 \phi_2}{\Sigma_1 \phi_1} \quad (B9)$$

to eliminate $\Sigma_2 \phi_2$, then

$$\begin{aligned}
x\Delta\rho^{\text{Cu}} &= \phi_2^+ (\text{CdR}^{\text{Cu}} - 1) \Sigma_1 \phi_1 + \phi_2^+ \frac{(\text{RI}_{\text{epi Cd}}^{\text{Cu}} - \text{RI}_{\text{ex}}^{\text{Cu}})}{\text{RI}_{\text{epi Cd}}^{\text{Cu}}} \Sigma_1 \phi_1 \quad (\text{B10}) \\
&+ \phi_1^+ \frac{\text{RI}_{\text{ex}}^{\text{Cu}}}{\text{RI}_{\text{epi Cd}}^{\text{Cu}}} \Sigma_1 \phi_1
\end{aligned}$$

$$= \phi_2^+ \text{CdR}^{\text{Cu}} - \text{RI}_{\text{ex}}^{\text{Cu}} (\phi_2^+ - \phi_1^+)$$

Dividing Equation B8 by Equation B10 gives

$$\Delta\rho^{\text{Cu}} - \Delta\rho^{\text{Cu}'} = \Delta\rho^{\text{Cu}} \frac{\phi_1^+ \text{RI}_{\text{ex}}^{\text{Cu}}}{\phi_2^+ \text{RI}_{\text{epi Cd}}^{\text{Cu}} \text{CdR}^{\text{Cu}} - \text{RI}_{\text{ex}}^{\text{Cu}} (\phi_2^+ - \phi_1^+)} \quad (\text{B11})$$

The correction c is then given by

$$c = \frac{\phi_1^+}{\phi_2^+} \frac{\text{RI}_{\text{ex}}^{\text{Cu}}}{\text{CdR}^{\text{Cu}} \text{RI}_{\text{epi Cd}}^{\text{Cu}} - \text{RI}_{\text{ex}}^{\text{Cu}} (1 - \frac{\phi_1^+}{\phi_2^+})} \quad (\text{B12})$$

Substitution of the quantities from Table XVI gives $c = .0434$, which is in reasonable agreement with the room temperature value calculated above since absorption in N_2 resonances is neglected in the latter method. Since the nitrogen is dilute, the copper absorption is expressed in terms of the dilute absorptions:

$$(\Sigma\phi V)^{\text{Cu}}_{\text{D}} = (\Sigma\phi V)^{\text{Cu}}_{\text{dil}} \quad (\text{B13})$$

where D is the disadvantage factor for the thickness of copper used and is determined as in Appendix A and presented in Table XVI. The ratio of the absorption in Equation B5 then reduces to:

TABLE XVI

CONSTANTS USED IN EVALUATION OF THE NITROGEN CORRECTION
AT ROOM TEMPERATURE

Cadmium Ratio (.010-inch copper)	8.942
Calculated Cadmium Ratio (.010-inch copper)	8.958
Disadvantage Factor D (.010-inch copper)	1.0110
RI_{ex}^{Cu} (.010-inch copper)	1.3705 b
$RI_{epi}^{Cu} Cd$ (.010-inch copper)	2.8805 b
ϕ_1^+ / ϕ_2^+	.8013
T_o	295°K
P_o	766.02 torr
V	$22.12 \times 10^3 \text{ cm}^3$
σ_a^N	1.88 b
σ_a^{Cu}	3.79 b
ξ^N	.136
σ_s^N	10.0 b
ξ^C	.158
σ_s^C	4.8 b
σ_a^C	$3.8 \times 10^{-3} \text{ b}$

$$\frac{(\Sigma\phi V)^{N_2}}{(\Sigma\phi V)^{Cu}} = \frac{M^{N_2}\sigma^N}{14.0} \frac{63.54}{M^{Cu}\sigma^{Cu}} \quad (B14)$$

where σ is the 2200 m/s cross section. Using the ideal gas law,

$$M^{N_2} = 28.0 \frac{PV}{RT} = 28.0 \frac{P_O V}{RT_O} \left(\frac{P}{P_O}\right) \left(\frac{T_O}{T}\right) \quad (B15)$$

where P_O and T_O are standard values at room temperature.

Substituting in Equation B5,

$$\Delta\rho_a^{N_2} = \frac{\Delta\rho^{Cu}}{M^{Cu}} (1-c) D \left(\frac{P}{P_O}\right) \left(\frac{T_O}{T}\right) \left(\frac{2P_O V}{RT_O}\right) \left(\frac{\sigma^N}{\sigma^{Cu}}\right) 63.54 \quad (B16)$$

$$\Delta\rho_a^{N_2} = 58.86 (1-c) D \left(\frac{P}{P_O}\right) \left(\frac{T_O}{T}\right) \left(\frac{\Delta\rho^{Cu}}{M^{Cu}}\right) \quad (B17)$$

If the atmosphere is air,

$$\Delta\rho_a^{air} = .7809 \Delta\rho_a^{N_2} \quad (B18)$$

The nitrogen also will moderate neutrons, thereby increasing their worth. The reactivity effect of the neutron scattering can be estimated from the measured graphite worth,

$$\Delta\rho_S^{N_2} = \frac{\Delta\rho^{G'}}{M^G} \frac{(\xi\sigma_s)^N}{(\xi\sigma_s)^C} \frac{12}{14} M^{N_2} \quad (B19)$$

where $\xi\sigma_s$ is taken as the effective moderating power and

the prime on the $\Delta\rho^G$ indicates that the measured value must be corrected for the graphite absorption. The reactivity worth of this absorption can be calculated in a manner similar to the nitrogen calculation above,

$$\begin{aligned}\Delta\rho_a^g &= \frac{\Delta\rho^{Cu}}{M^{Cu}} (1-c) M^g \frac{\sigma^C}{\sigma^{Cu}} \frac{63.54}{12} D \\ &= 5.13 \times 10^{-3} \frac{\Delta\rho^{Cu}}{M^{Cu}}\end{aligned}\quad (B20)$$

Using the room temperature value of $\Delta\rho^{Cu}/M^{Cu}$ of $-.0215 \text{ } \phi/\text{gm}$, $\Delta\rho_a^g$ is found to be $-.110 \times 10^{-3} \text{ } \phi/\text{gm}$. The measured $\Delta\rho^g$ is 0.638×10^{-3} so $\Delta\rho^g$ is found to be $0.748 \times 10^{-3} \text{ } \phi/\text{gm}$.

Using Equation B13 and the values in Table XV.

$$\Delta\rho_s^{N_2} = 40.0 \left(\frac{\Delta\rho^g}{M^g} \right) \left(\frac{P}{P_o} \right) \left(\frac{T_o}{T} \right) \quad (B21)$$

At room temperature $\Delta\rho_s^{N_2}$ is about $.030\phi$ which is quite small. Combining Equation B21 with Equation B17, for room temperature

$$\Delta\rho^{N_2} = \left[58.86 \left(\frac{\Delta\rho^{Cu}}{M^{Cu}} \right) (1-c) D - 40.0 \left(\frac{\Delta\rho^g}{M^g} \right) \right] \left(\frac{P}{P_o} \right) \left(\frac{T_o}{T} \right) \quad (B22)$$

However, since $\Delta\rho^{Cu}$ and $\Delta\rho^g$ do not change by a large amount as a function of temperature, and since the scattering term is so small, one can write to a good approximation,

$$\Delta\rho^{g'}(T) = \Delta\rho^{Cu}(T) \frac{\Delta\rho^g(T_o)}{\Delta\rho^{Cu}(T_o)} = .0360 \frac{\Delta\rho^{Cu}(T)}{M^{Cu}} (1-c) M^g \quad (B23)$$

and thus

$$\Delta\rho^{N_2} = 57.42 (1-c) D \left(\frac{\Delta\rho^{Cu}}{M^{Cu}} \right) \left(\frac{P}{P_o} \right) \left(\frac{T_o}{T} \right) \quad (B24)$$

For air the magnitude of the scattering effect is lowered about 12%. Thus,

$$\Delta\rho^{\text{air}} = \left[45.96 \frac{\Delta\rho^{\text{Cu}}}{M^{\text{Cu}}} (1-c) D - 35.2 \left(\frac{\Delta\rho^{\text{g}}}{M^{\text{g}}} \right) \right] \left(\frac{P}{P_0} \right) \left(\frac{T}{T_0} \right)$$

$$= 44.70 \left(\frac{\Delta\rho^{\text{Cu}}}{M^{\text{Cu}}} \right) (1-c) D \left(\frac{P}{P_0} \right) \left(\frac{T}{T_0} \right)$$

The values from Equation B25 at room temperature and

Equation B24 for each temperature are displayed in Table XVII.

The scattering term is shown separately to illustrate its magnitude in comparison with the absorption term.

TABLE XVII
NITROGEN CORRECTION

T	T ₀ /T	P/P ₀	$\Delta\rho^{\text{Cu}}/\text{M}^{\text{Cu}}$	$\Delta\rho_{\text{a}}$	$\Delta\rho_{\text{s}}$	$\Delta\rho^{\text{N}_2}$
20 Air	.997	.949	.02176	.919	.025	.894
20 N ₂	1.000	.981	.02124	1.190	.029	1.161
150	.697	1.0	.02124	.845	.021	.844
300	.515	1.0	.02162	.634	.015	.619
500	.382	1.0	.02074	.450	.011	.439
750	.288	1.0	.01957	.321	.009	.312
1000	.232	1.0	.01983	.261	.007	.254

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