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AEC Research and Development Report

MEASUREMENT OF K_{∞}
AS A FUNCTION OF TEMPERATURE
FOR A $^{233}\text{UO}_2$ - $^{232}\text{ThO}_2$ - C LATTICE

February 1972

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MEASUREMENT OF K_{∞} AS A FUNCTION OF TEMPERATURE

FOR A $^{233}\text{UO}_2$ - $^{232}\text{ThO}_2$ - C LATTICE

by

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MEASUREMENT OF k_{∞} AS A FUNCTION OF TEMPERATURE FOR A $^{233}\text{UO}_2$ - $^{232}\text{ThO}_2$ - C LATTICE

Introduction

The third measurement of a series performed in support of the High Temperature Gas Cooled Reactor (HTGR) Program as a part of the General Reactor Technology Program of the USAEC has been completed. The temperature dependence of the neutron multiplication factor, k_{∞} , of a $^{233}\text{UO}_2$ - $^{232}\text{ThO}_2$ - C test lattice was determined between room temperature and 1000°C in the High Temperature Lattice Test Reactor (HTLTR) at the Pacific Northwest Laboratory.

The test lattices in this series have been selected to obtain neutronic data over a range of C/U and C/Th ratios, thus providing a set of benchmarks for use in testing and evaluating the computational methods being employed in HTGR design studies.

Description of the Test Lattice

Each fuel element consisted of a $3\frac{3}{4} \times 3\frac{3}{4} \times 24$ -inch graphite block with twenty-five fuel channels (0.470-inches diameter) equally spaced in a 5×5 array of $\frac{3}{4}$ -inch pitch. The individual fuel channels were filled with a mixture of graphite powder, ThO_2 powder and pyrolytic carbon coated ThO_2 - UO_2 particles. The oxide microspheres,

which were prepared and coated at the Oak Ridge National Laboratory, were $(^{232}\text{Th} - 25\% ^{233}\text{U})\text{O}_2$, with a diameter of $\sim 320 \mu$ and a coating thickness of $\sim 100 \mu$. The as-loaded atom ratios for the four-block central cell were:

$$\frac{C}{\text{Th}} \sim 278 \text{ and } \frac{C}{^{233}\text{U}} \sim 13756$$

The average composition of the centrally located four cell blocks is given in Table I. The isotopic composition of the uranium contained in the oxide microspheres is given in Table II.

The fuel elements were arranged in the HTLTR as shown in Figure 1. The central region of the reactor was filled with an 8×8 array of fuel blocks. Proceeding toward the front and rear faces of the reactor the test lattice was stepped down to a 4×4 array, and finally, a 2×2 array which extended over the full 10-foot length of the reactor.

External to the test lattice, the reactor was loaded with short end drivers adjacent to the ends of the test lattice and, radially, with driver fuel, buffer fuel and temperature compensating shims as appropriate to provide sufficient reactivity for reactor operations and to adjust the neutron spectrum incident on the test lattice to simulate an infinite array of the test lattice cells.

TABLE I

COMPOSITION OF $^{233}\text{UO}_2$ - $^{232}\text{ThO}_2$ - C FUEL BLOCKS
(CONCENTRATIONS IN ATOMS/BARN-CM)

<u>Isotope</u>	<u>Graphite Powder</u>	<u>Moderator</u>	<u>(U,Th)O_2 Particle</u>	<u>ThO_2 Powder</u>
Carbon	4,9112 - 02	8.1114 - 02	- - -	
Oxygen	- - -	- - -	4.5634 - 02	4.5636 - 02
Nitrogen	2,8299 - 05*	1,4093 - 05*	- - -	- - -
^{233}U	- - -	- - -	5,5419 - 03	- - -
^{234}U	- - -	- - -	5.9052 - 05	- - -
^{235}U	- - -	- - -	5,4766 - 06	- - -
^{236}U	- - -	- - -	3.3749 - 07	- - -
^{238}U	- - -	- - -	7.9838 - 05	- - -
^{232}Th	- - -	- - -	1.7131 - 02	2.2818 - 02

*20°C only

TABLE II

ISOTOPIC COMPOSITION OF URANIUM IN OXIDE MICROSPHERES

<u>Isotope</u>	<u>wt%</u>
^{233}U	97.42 $\pm$ 0.9
^{234}U	1.042 $\pm$ 0.001
^{235}U	0.097 $\pm$ 0.0001
^{236}U	0.006 $\pm$ 0.00006
^{238}U	1.43 $\pm$ 0.001

FIGURE 1: TEST LATTICE CONFIGURATION WITHIN HTLTR

Experimental Techniques and Results

A. The Unpoisoned Technique for Determining k'_{∞}

The unpoisoned method^(1,2,3) for determining k'_{∞} is based on observing the reactivity worth of a sample of the multiplying medium (the central cell) and a normalization of this result to the reactivity worth of a thermal neutron absorber, e.g., copper. The parameter to be determined, k'_{∞} , is evaluated using:

$$k'_{\infty} = 1 - \left(\frac{\Delta\rho^{\text{cell}}}{\Delta\rho^{\text{abs}}} \right) \left(\frac{\left(\Sigma_a v\phi \right)_2^{\text{abs}}}{\left(\Sigma_a v\phi \right)_2^{\text{cell}}} \right) \left(1 + \left[\frac{\phi_1^+}{\phi_2^+} \right] \frac{\left(\Sigma_a \phi \right)_1^{\text{abs}}}{\left(\Sigma_a \phi \right)_2^{\text{abs}}} \right) - f_1 (L^2 B^2) + f_2 (\tau B^2) + g(\phi, \phi^+) \quad (1)$$

where: $\frac{\Delta\rho^{\text{cell}}}{\Delta\rho^{\text{abs}}} =$ Ratio of the reactivity worth of the sample of the multiplying medium to the reactivity worth of the absorber.

$\frac{\left(\Sigma_a v\phi \right)_2^{\text{abs}}}{\left(\Sigma_a v\phi \right)_2^{\text{cell}}} =$ Ratio of the relative thermal reaction rate of the absorber to that of the cell

$\left[\frac{\phi_1^+}{\phi_2^+} \right] =$ Ratio of the adjoint fluxes evaluated in the cavity.

$\frac{\left(\Sigma_a \phi \right)_1^{\text{abs}}}{\left(\Sigma_a \phi \right)_2^{\text{abs}}} =$ Ratio of the relative reaction rate in the absorber (epithermal-to-thermal).

$f_1(L^2B^2)$, $f_2(\tau B^2)$ are correction terms for finite leakage present in the unpoisoned lattice.⁽¹⁾

$g(\phi, \phi^+)$ is a correction term for the direct and adjoint flux spectra which may differ in the HTLTR array from that present in a just critical sphere of the multiplying medium.⁽¹⁾

B. Reactivity Measurements

Ideally, the required reactivity measurements should be made with a reactor loading where the spectrum is everywhere the same throughout the test core. Therefore, following the loading to critical of HTLTR, a series of gold foil cadmium ratio measurements were made, radially and axially, throughout the test core to determine, as a function of the reactor loading, when the spectrum deviation was minimized. After achieving the optimum loading, reactivity worths were obtained for the 4-block central cell, a single fueled block and a copper absorber, at room temperature and subsequently at temperature levels of 150, 300, 555, 700, and 1000°C.

The 4-block central cell consists of four $^{233}\text{UO}_2$ - $^{232}\text{ThO}_2$ - C fueled blocks located at the center of the test lattice as shown in Figure 1. These four blocks are connected to a rearward extending fuel train which can be moved to the rear and create a cavity (7-1/2 x 7-1/2 x 24 inches). In order to obtain $\Delta\rho^{\text{cell}}(T)$, reactivity measurements were made consisting of: $\rho(\text{cell in})$ and $\rho(\text{cell out})$.

Then: $\Delta\rho^{\text{cell}}(T) = \rho(\text{cell in}) - \rho(\text{cell out})$

where: $\rho(\text{cell in})$ = measured reactivity with the 4-block cell in place at the center of the test lattice.

$\rho(\text{cell out})$ = measured reactivity with the 4-block cell retracted rearward by 24 inches to create a cavity at the center of the test lattice.

$\Delta\rho^{\text{cell}}$ = reactivity worth of the 4-block central cell.

In order to obtain $\Delta\rho^{\text{abs}}(T)$, the cell out condition was created and the copper absorber was introduced into the cavity from the front via a single block fuel train. The copper absorber was placed in a graphite carrier for ease in handling at elevated temperatures. The reactivity measurements taken were: $\rho(\text{Cu absorber} + \text{carrier in void})$ and $\rho(\text{carrier only})$. Then:
 $\Delta\rho^{\text{abs}}(T) = \rho(\text{Cu absorber} + \text{carrier}) - \rho(\text{carrier only})$.

where: $\rho(\text{Cu absorber} + \text{carrier})$ = measured reactivity with copper absorber and carrier in place in the cavity.

$\rho(\text{carrier only})$ = measured reactivity with the carrier only in place in the cavity.

$\Delta\rho^{\text{abs}}$ = reactivity worth of the copper absorber.

At room temperature, where easy access to the cavity is possible, it was determined that the measured worth of the copper was the same within the precision of the measurement whether placed on the carrier or placed separately in the cavity.

The values of the reactivities measured at each temperature level are given in Table III. Values at room temperature are given both for the air atmosphere and the N₂ atmosphere. The evaluations of $\Delta\rho^N$, $\Delta\rho^{ext}$, and $\Delta\rho_{caps}^{end}$ are described in an Appendix.

The measured room temperature value for the worth of copper in the nitrogen atmosphere is indicated by the consistency of the data to be low relative to the air measurement. A minor loading change was made when the nitrogen atmosphere was established which increased the sensitivity at the reactor center. When this effect is included, the ratio of central cell worth to copper worth is the same within error for both measurements. Therefore, an average room temperature value is used.

The values of $\frac{\Delta\rho^{cell}}{\Delta\rho^{abs}}(T)$ and $\frac{\Delta\rho^{single\ block}}{\Delta\rho^{abs}}(T)$ as obtained in this experiment are shown in Figure 2, and are also tabulated in Table III.

Of the measured quantities in Equation (1) for k'_{∞} , only the reactivity ratio $\Delta\rho^{cell}/\Delta\rho^{abs}$ could be measured as a function of temperature. This was due to the fact that, at elevated temperatures, the reactor enclosure was sealed and an inert gas atmosphere had to be maintained within this enclosure. Thus, the reactor interior was inaccessible for purposes of foil irradiations necessary for the determination of relative reaction rates.

TABLE III

REACTIVITY DATA MEASURED AT EACH TEMPERATURE LEVEL

T (°C)	$\Delta\rho_{\text{abs}}^{(a)}$	$\Delta\rho_{\text{graphite carrier}}^{(a)}$	$\Delta\rho_{\text{cell uncorr.}}^{(a)}$	$\Delta\rho_{\text{N}}^{(a)}$	$\Delta\rho_{\text{ext}}^{(a)}$	$\Delta\rho_{\text{end caps}}^{(a)}$	$\Delta\rho_{\text{cell corr.}}^{(a)}$	$\left(\frac{\Delta\rho_{\text{cell corr.}}}{\Delta\rho_{\text{abs}}}\right)$	$\left(\frac{\Delta\rho_{\text{single block corr.}}}{\Delta\rho_{\text{abs}}}\right)$
20 (air)	4.874	0.797	6.410	-0.985	0.368	0.940	4.853	$1.002 \pm 0.026^{(b)}$	$0.282 \pm 0.011^{(b)}$
20 (N ₂)	4.873	0.757	6.850	-1.353	0.368	0.940	4.925		
150	4.830	0.836	6.153	-0.929	0.368	0.996	4.596	0.952 ± 0.060	0.245 ± 0.025
300	4.701	0.950	5.592	-0.668	0.368	1.048	4.244	0.903 ± 0.048	0.256 ± 0.026
555	4.584	0.829	5.520	-0.451	0.368	1.129	4.308	0.940 ± 0.053	0.258 ± 0.030
700	4.542	0.963	5.559	-0.380	0.368	1.166	4.381	0.965 ± 0.065	0.258 ± 0.032
1000	4.441	1.017	5.859	-0.276	0.368	1.392	4.559	1.027 ± 0.082	0.257 ± 0.038

(a) Reactivities are given in cents. The experimental uncertainty of each reactivity measurement has been determined to be ± 0.03 at room temperature, ± 0.05 at temperatures between 300°C and 700°C, and ± 0.07 at 150°C and 1000°C.

(b) The room temperature measurements (not all presented here) indicate that the copper reactivity in N₂ should be higher relative to the measurement in air, and that $(\Delta\rho^{\text{cell}}/\Delta\rho^{\text{abs}})$ should be the same for the two measurements. Accordingly, an average room temperature value is used in the subsequent calculations.

FIGURE 2: VALUES OF 4-BLOCK AND SINGLE BLOCK CELLS

C. Relative Reaction Rate Measurements at Room Temperature

Relative reaction rates of the test cell components were determined from foil activation measurements at room temperature only. Energy dependence of the reaction rates was determined from cadmium ratios. Bare and cadmium covered foils were activated in separate irradiations and were normalized by simultaneous irradiation of monitor foils in a highly thermalized location near the edge of the HTLTR. A special block was used for these foil irradiations which permitted the inclusion of Cu, and (U,Th) O_2 foils in either of two fuel channels. Copper foils were placed on the axial and radial surfaces of the central cell. The specific activities of these foils were calculated using program APDAC-1⁽⁴⁾ which corrects the counting data for decay during counting, room background, foil mass variations and residual activity.

The corrections made to the foil activation data to account for the flux perturbation in the vicinity of a foil due to the presence of such a foil⁽⁵⁾ are presented in an Appendix.

The relative thermal neutron absorption rates in the 4-block central cell and single block, as inferred from room temperature foil activation data, are presented in Table IV.

The relative neutron absorption rates in the copper absorber as inferred from room temperature foil activation data, for each energy group being considered, are presented in Table V.

TABLE IV

RELATIVE THERMAL NEUTRON ABSORPTION RATES IN THE TEST SAMPLES

Region	Isotope	$\left[\frac{(\sum_a V\phi)_2^i}{\phi_o} \right]_{\text{cell}}^{4\text{-block}}$	$\left[\frac{(\sum_a V\phi)_2^i}{\phi_o} \right]_{\text{block}}^{\text{single}}$
Oxide Microspheres ↓	^{233}U	94.47185	23.18028
	^{234}U	0.16332	0.04081
	^{235}U	0.10487	0.02566
	^{236}U	0.00006	0.00001
	^{238}U	0.00065	0.00159
	^{232}Th	3.75164	0.92053
	^{16}O	0.00024	0.00006
ThO ₂ Powder ↓	^{232}Th	58.73647	14.62748
	^{16}O	0.00283	0.00070
Carbon (Including PyC) ↓	^{12}C	1.82682	0.45679
	^{14}N	0.51247	0.12814
Carbon Moderator ↓	^{12}C	6.94622	1.73658
	^{16}N	0.58754	0.14689
		167.1 ± 2.4	41.27 ± 0.58

$$\text{and, } \frac{(\sum_a V\phi)_2^{\text{abs}}}{(\sum_a V\phi)_2^{4 \text{ block cell}}} = 0.0722 \pm 0.0019$$

$$\frac{(\sum_a V\phi)_2^{\text{abs}}}{(\sum_a V\phi)_2^{\text{single block}}} = 0.292 \pm 0.008$$

TABLE V

RELATIVE NEUTRON ABSORPTION RATES IN THE COPPER ABSORBER

Group	$\frac{(\sum_a V\phi)_1^{abs}}{\phi_o^{monitor}}$
1	1.135 ± 0.510
2	12.06 ± 0.27

and,

$$\frac{(\sum_a \phi)_1^{abs}}{(\sum_a \phi)_2^{abs}} = 0.094 \pm 0.04$$

D. Relative Reaction Rates as a Function of Temperature

Since the central cell was inaccessible for conducting foil irradiations at elevated temperatures, another method was devised to generate the quantity $[(\sum_a V\phi)_2^{abs}/(\sum_a V\phi)_2^{cell}](T)$ using the following expression:

$$\left[\frac{(\sum_a V\phi)_2^{abs}}{(\sum_a V\phi)_2^{cell}} (T) \right] = \left\{ \left[\frac{(\sum_a V\phi)_2^{abs}}{(\sum_a V\phi)_2^{cell}} (20^\circ) \right]^{Foil} \left(\frac{\bar{\sigma}_a(T)}{\bar{\sigma}_a(T_o)} \right)_2^{Cu} \right. \\ \left. \left(\frac{\bar{\sigma}_a(T_o)}{\bar{\sigma}_a(T)} \right)_2^{cell} \left[\frac{\bar{\phi}_2^{void}(T)}{\bar{\phi}_2^{cell}(T)} \right] \left[\frac{\bar{\phi}_2^{cell}(T_o)}{\bar{\phi}_2^{void}(T_o)} \right] \right\} \quad (2)$$

where:

$$\left[\frac{(\Sigma_a \phi)_2^{abs}}{(\Sigma_a \phi)_2^{cell}} (20^\circ C) \right]^{Fol1s} = \text{the relative reaction rate ratio as determined experimentally via foil irradiations.}$$

$$\bar{\sigma}_a(T_o)_2^{Cu} = \text{spectrum averaged microscopic thermal neutron absorption cross section for copper at the surface of the central cell at } T_o = 20^\circ C. \text{ This value is obtained from:}$$

$$\sigma_a(T)_2^{Cu} = \sigma_{a_o}^{Cu} \times \sigma_{1/v}^{surface}(T)$$

where $\sigma_{1/v}^{surface}(T)$ is obtained from GRANIT. (6)
 GRANIT is a modified version of BRT-1 code which contains special collision probability calculations to treat this granular type fuel.

$$\bar{\sigma}_a(T)_2^{Cu} = \sigma_{a_o}^{Cu} \times \sigma_{1/v}^{surface}(T) = \text{spectrum averaged thermal neutron absorber cross section for copper at the surface of the central cell as a function of temperature.}$$

$$\Sigma_a(T_o)_2^{cell} = \text{macroscopic thermal neutron absorption cross section for the central cell at } T_o = 20^\circ C. \text{ This parameter is obtained from GRANIT.}$$

$$\Sigma_a(T)_2^{cell} = \text{macroscopic thermal neutron absorption cross section for the central cell as a function of temperature.}$$

$$\phi_2^{void}(T) = \text{average value of the thermal neutron flux in the void as a function of temperature. This value is obtained from a 2-dimensional HTLTR calculational model which utilizes a multigroup diffusion code - 2 DB. (8)}$$

-cell
 $\phi_2(2)$ = average value of the thermal
 neutron flux in the central
 cell as a function of temperature
 - 2 DB.

-void -cell
 $\phi_2(T_o), \phi_2(T_o)$ = Same as preceeding two entries
 except that value is for
 $T_o = 20^\circ\text{C}$.

The inferred values of the relative reaction
 rate ratios as a function of temperature are presented
 in the second and third column of Table VI.

TABLE VI

INFERRED ABSORPTION RATE RATIOS AS A FUNCTION OF TEMPERATURE

Temperature (°C)	$\frac{(\sum_a V\phi)_2^{\text{abs}}}{(\sum_a V\phi)_2^{\text{cell}}} (T)$	$\frac{(\sum_a V\phi)_2^{\text{abs}}}{(\sum_a V\phi)_2^{\text{block}}} (T)$	$\frac{(\sum_a \phi)_1^{\text{abs}}}{(\sum_a \phi)_2^{\text{abs}}} (T)$
150	0.071639	0.29012	0.09803
300	0.071454	0.28937	0.10148
555	0.071002	0.28754	0.10641
700	0.070712	0.28636	0.10931
1000	0.070160	0.28413	0.11385

Similarly, the ratio $\frac{(\Sigma_a \phi)_1^{abs}}{(\Sigma_a \phi)_2^{abs}}$ was also required as a function of temperature and the expression used for this purpose was:

$$\left[\frac{(\Sigma_a \phi)_1^{abs}}{(\Sigma_a \phi)_2^{abs}}(T) \right] = \left\{ \left[\frac{(\Sigma_a \phi)_1^{abs}}{(\Sigma_a \phi)_2^{abs}}(20^\circ\text{C}) \right]^{Foil} \left(\frac{\bar{\sigma}_a(T_o)}{\bar{\sigma}_a(T)} \right)_2^{Cu} \right. \\ \left. \left(\frac{RI_{eff}^{Cu}(T)}{RI_{eff}^{Cu}(T_o)} \right) \left[\frac{\phi_1^{void}(T)}{\phi_2^{void}(T)} \right] \left[\frac{\phi_2^{void}(T_o)}{\phi_1^{void}(T_o)} \right] \right\} \quad (3)$$

where: $\left[\frac{(\Sigma_a \phi)_1^{abs}}{(\Sigma_a \phi)_2^{abs}}(20^\circ\text{C}) \right]^{Foil}$ = the relative reaction rate ratio as determined experimentally via foil irradiations.

$$\bar{\sigma}_a(T_o)_2^{Cu}, \bar{\sigma}_a(T)_2^{Cu} = \text{see above}$$

$RI_{eff}^{Cu}(T)$ = effective resonance integral of copper as a function of temperature, This value is obtained from EGGNIT.⁽⁹⁾ EGGNIT is a slowing down code which can treat the particle type fuel used in this lattice.

$RI_{eff}^{Cu}(T_o)$ = effective resonance integral of copper at $T_o = 20^\circ\text{C}$, obtained from EGGNIT.

$\phi_1^{void}(T)$ = average value of the epithermal neutron flux in the void as a function of temperature, obtained from 2 DB model calculation.

$\phi_2^{void}(T)$ = average value of the thermal neutron flux in the void as a function of temperature, obtained from 2 DB.

$\phi_2^{void}(T_o), \phi_1^{void}(T_o)$ = same as preceding two entries except that value is for $T_o = 20^\circ\text{C}$.

The inferred values of these ratios as a function of temperature are presented in the fourth column of Table VI.

E. Neutron Cross Sections

Cross sections and group constants required for obtaining the relative reaction rates in Equation (1) were generated, for the thermal group, by using GRANIT⁽⁶⁾ and, for the epithermal group, by using EGGNIT.⁽⁹⁾

The thermal parameters obtained are shown in Table VII and in the second and third columns of Table VIII. GRANIT,⁽⁶⁾ a modified version of BRT-1,⁽⁷⁾ employs a special geometry routine to treat the particle self shielding problem which occurs in the situation where granular particles, both (U,Th)O₂ and ThO₂, are present in the fuel mixture. For the thermal calculations the unit cell is treated in cylindrical geometry consisting of an inner fuel mixture region and an annular moderating region with reflecting cell boundary conditions.

The epithermal group parameters obtained are given in the third and fourth column of Table VIII. The epithermal group values were computed by EGGNIT⁽⁹⁾ slowing down code using the B₁ approximation. Resonance self shielding was treated by an exact integration scheme in the granular fuel geometry typical of this fuel mixture.

Additional calculated epithermal parameters are given in Table IX.⁽⁹⁾

TABLE VII

SPECTRUM AVERAGED MICROSCOPIC THERMAL ABSORPTION CROSS SECTIONS (BARNs)

Temperature °C	Moderator		Graphite Powder		ThO ₂ Powder	
	$\begin{pmatrix}^{12}\text{C} \\ (\times 10^{-3})\end{pmatrix}$	^{14}N	$\begin{pmatrix}^{12}\text{C} \\ (\times 10^{-3})\end{pmatrix}$	^{14}N	^{232}Th	$\begin{pmatrix}^{16}\text{O} \\ (\times 10^{-4})\end{pmatrix}$
20	2.35817	1.28312	2.35501	1.28140	5.12598	1.23282
150	2.16554	1.17831	2.16301	1.17693	4.70831	1.13232
300	1.92774	1.04892	1.92589	1.04791	4.19250	1.00821
555	1.68111	0.91472	1.67890	0.91401	3.65722	0.87939
700	1.57304	0.85592	1.57194	0.85532	3.42261	0.82293
1000	1.40812	0.76618	1.40731	0.76574	3.06455	0.73675

(U,Th)O₂ Microspheres

	$\begin{pmatrix}^{16}\text{O} \\ (\times 10^{-4})\end{pmatrix}$	^{232}Th	^{233}U	^{234}U	^{235}U	^{236}U	^{238}U
20	1.22297	5.08502	395.813	65.3969	443.335	3.80640	1.88454
150	1.12427	4.67483	363.705	60.1380	401.794	3.35004	1.73600
300	1.00216	4.16736	324.895	53.6359	353.206	2.83551	1.55301
555	0.87498	3.63887	285.541	46.87000	305.783	2.36104	1.36356
700	0.81916	3.40692	268.583	43.90290	285.477	2.16963	1.28086
1000	0.73387	3.05257	243.039	39.3737	254.084	1.89621	1.15519

TABLE VIII

THERMAL AND EPITHERMAL GROUP PARAMETERS OF THE TEST CELL

Temperature °C	$\Sigma_{a_2}^{\text{cell}} \times 10^{-3}$	$v\Sigma_{f_2}^{\text{cell}} \times 10^{-3}$	$\Sigma_{a_1}^{\text{cell}} \times 10^{-3}$	$v\Sigma_{f_1}^{\text{cell}} \times 10^{-3}$
20	3.48517	4.49812	0.91303	0.54045
150	3.20033	4.13837	0.94767	0.53925
300	2.85684	3.70510	0.97832	0.53809
555	2.50457	3.26887	1.0168	0.53587
700	2.35220	3.08188	1.0345	0.53534
1000	2.12061	2.80041	1.0649	0.53570

TABLE IX

CALCULATED EPITHERMAL PARAMETERS

Temperature °C	$\Sigma_{1 \rightarrow 2}^{\text{cell}} \times 10^{-2}$	p	$RI_a^{232\text{Th}}$	$RI_a^{233\text{U}}$	$RI_f^{233\text{U}}$
20	0.25653	0.73751	39.161	748.995	620.903
150	0.25525	0.72925	41.457	750.367	622.014
300	0.25411	0.72202	43.484	751.408	622.832
555	0.25247	0.71290	46.063	751.876	623.135
700	0.25167	0.70870	47.234	753.032	624.079
1000	0.25016	0.70142	49.218	757.437	627.771

F. Flux Calculations

Direct and adjoint flux ratios required in the analysis (Equations (1), (2), and (3)) were generated with a two-dimensional model of HTLTR in R-Z geometry using the multigroup diffusion code 2 DB.⁽⁸⁾ The as-loaded reactor was mocked up in this model and two group direct and adjoint flux calculations were performed for the reactor with a cell in place and the reactor with a cavity at its center. In order to compensate for the inability of the diffusion code to deal with a voided region, transport theory calculations were used to verify that a pseudo scattering medium (zero capture, no moderation) was a reasonable replacement for the cavity region in the model calculations.

Due to the rather homogeneous nature of the fuel blocks, the radial flux distribution through the central cell is essentially flat. However, the axial flux distribution showed the effect of the front and rear graphite end caps and the average flux in the cell (or cavity) was determined by volume weighting the calculated flux over the length of the fueled portion of the cell, i.e.,

$$\bar{\phi} = \sum_i \frac{V_i \phi_i}{V_i}$$

G. Determination of k'_{∞}

Using the unpoisoned method for determining k'_{∞} the expression, Equation (1), can be rewritten as:

$$k'_{\infty} = k_{\text{UNCORR}}^{\text{EXP}} - f_1(L^2B^2) + f_2(\tau B^2) + g(\phi, \phi^+) \quad (4)$$

where:

$k_{\text{UNCORR}}^{\text{EXP}}$ is the measured value determined from the HTLTR experiment.

The measured values of $k_{\text{UNCORR}}^{\text{EXP}}$, the calculated values of the leakage and mismatch correction factors, and the resulting values of k'_{∞} for the various loadings as a function of temperature are given in Table X. The correction factors have been calculated using a value for the buckling consistent with the experimental k'_{∞} . The values of k'_{∞} - both measured and calculated - are shown in Figure 3.

The value of k'_{∞} as calculated via the two group formulation⁽³⁾ shown below is also given in the last column of Table X.

$$k'_{\infty} = \frac{v_1 \Sigma_1^f \left(\frac{\phi_1}{\phi_2} \right) + v_2 \Sigma_2^f}{\Sigma_1^a \left(\frac{\phi_1}{\phi_2} \right) + \Sigma_2^a} \quad (4a)$$

In this expression, the thermal and epithermal group parameters were obtained from GRANIT⁽⁶⁾ and EGGNIT⁽⁹⁾ respectively. The flux ratio was obtained from HFN,⁽¹⁰⁾

These results, for both the measured and calculated values of k'_{∞} are dependent upon the calculational methods and the cross section libraries currently employed at Battelle Northwest.

FIGURE 3: VALUES OF K'_∞ MEASURED AND CALCULATED

TABLE X

EXPERIMENTAL AND CALCULATED PARAMETERS
AS A FUNCTION OF TEMPERATURE

T °C	$k_{\text{uncorr.}}^{\text{exp}}$ (4 block cell)	$f_1(L^2B^2)$	$f_2(\tau B^2)$	$g(\phi, \phi^+)$	k_{∞}' (4 block cell)	k_{∞}' (single cell)	k_{∞}' Calculated
20	1.0780 ± 0.0041	0.0089	-0.0054	0.0002	1.064 ± 0.005	1.065 ± 0.006	1.101
150	1.0736 ± 0.0056	0.0091	-0.0050	0.0003	1.060 ± 0.006	1.063 ± 0.009	1.0904
300	1.0656 ± 0.0047	0.0097	-0.0046	0.0000	1.055 ± 0.006	1.066 ± 0.009	1.0824
555	1.0725 ± 0.0051	0.0108	-0.0045	-0.0005	1.057 ± 0.006	1.065 ± 0.010	1.0746
700	1.0742 ± 0.0059	0.0116	-0.0045	-0.0008	1.057 ± 0.007	1.063 ± 0.011	1.0719
1000	1.0786 ± 0.0071	0.0133	-0.0045	-0.0012	1.060 ± 0.008	1.061 ± 0.013	1.0686

Conclusions

The parameters for this third experiment with an HTGR type fuel were selected so as to minimize the Δk_{∞} as a function of temperature. Experimentally, the results indicate that the desired effect was achieved, i.e., the k_{∞} of the $^{233}\text{UO}_2 - \text{ThO}_2 - \text{C}$ fuel chosen exhibited no change within error over the temperature range being investigated. However, a value of $\Delta k_{\infty} = - 0.0324$ over the range from 20°C to 1000°C was obtained via the calculational method.

The lack of agreement between the calculated and measured values is disappointing and is not adequately explained by experimental or analytical errors. Since both the measurement and the calculations are dependent upon calculational methods and cross section libraries currently in use at Battelle Northwest it may be concluded that an experiment theory correlation would be a worthwhile task using these data. It should be noted that the observed in-reactor behavior of a test sample (as normalized with the absorber), see Figure 2, is direct evidence of the temperature dependence of this fuel material.

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Appendix

A. Reactivity Measurements

1. Nitrogen Corrections

The HTLTR, when operated at elevated temperatures and for some room temperature measurements, was contained within a sealed enclosure with a nitrogen atmosphere maintained at a pressure slightly greater than atmospheric. When the enclosure is opened at room temperature the nitrogen was, of course, replaced by air. Nitrogen, either as the blanket gas or as the principal component of air, affects the reactivity measurements in two ways: (1), nitrogen (or air) occupies the natural voids occurring the reactor graphite and acts as a parasitic absorber; and (2), when the central cell fuel train is moved rearward to create the cavity, nitrogen (or air) enters and fills this cavity. To obtain corrected reactivity values for the samples in a vacuum environment the reactivity worth of the nitrogen (or air) must be removed.

The reactivity worth of nitrogen, $\Delta\rho^N$, was inferred from the measurement of the copper sensitivity, S^{Cu} , and the expression:

$$\Delta \rho^N = DC \frac{P}{T} M_N (1-c) S^{Cu}$$

where:

D = Thermal disadvantage factor for 0.010-inch thick Cu as used in determining $S^{Cu} = 1.0110$

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

$$\sigma_{a_o}^N = 1.88b$$

$$\sigma_{a_o}^{Cu} = 3.79b$$

A^{Cu}, A^N = atomic weights of copper and nitrogen

T_o, P_o = standard temperature and pressure

P = nitrogen (or air) pressure during reactivity measurements, torr.

T = temperature in void during reactivity measurements, °K.

M_N = mass of nitrogen (or nitrogen in air) in the cavity at STP.

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

$$(1-c) = 1 - \left[\frac{\phi_1^+}{\phi_2^+} \right] \frac{Rl_{ex}^{Cu}}{Rl_{epi-Cd}^{Cu} (CdR^{Cu} - 1)}$$

$\frac{\phi_1^+}{\phi_2^+}$ = fast to thermal adjoint ratio in the cavity 2 DB calculation.

RI_{ex}^{Cu} = effective excess resonance integral of 0.010-inch thick natural copper = 1.3705b.

RI_{epi-Cd}^{Cu} = effective epi-Cd resonance integral of 0.010-inch thick natural copper = 2.8805b.

CdR^{Cu} = measured cadmium ratio of 0.010-inch thick copper in the cavity.

S^{Cu} = sensitivity of 0.010-inch thick copper strip in the cavity, ϵ/gm .

$$= \frac{\Delta\rho^{Cu}}{Mass^{Cu}}$$

2. Temperature Corrections

When the HTLTR was heated to an elevated temperature, sufficient time had to be allowed for the system to come to thermal equilibrium at the desired temperature. Normally, the central cell out condition was created and the samples to be measured (single fueled block, absorber and carrier, carrier only) were introduced via the front fuel train after being preheated in an external device. The reactivity of the newly introduced sample was observed to vary with time as the sample and its surroundings came into thermal equilibrium. The observed reactivity together with the reactor temperature, as measured by a RTD located near the test sample, was monitored until minimal changes in both parameters were noted. The resulting values of both reactivity and temperature were then assumed to be representative of the test sample being investigated.

3. HTLTR Reactivity Coefficients

The HTLTR temperature and pressure coefficients were determined at each equilibrium temperature and the observed reactivity values were pressure and temperature corrected to a common reference condition prior to determining $\Delta\rho$ values.

4. Central Cell Extension Correction

When the central cell was moved rearward to create the cavity, a 7-1/2 x 7-1/2 x 24-inch fueled extension was created through the rear reactor face. Thus, when one determines the cell worth by this method the value actually obtained is the worth of a cell with an extension, i.e.,

$$\Delta\rho_{w/extension}^{cell} = \rho(\text{cell in}) - \rho(\text{cell out; with extension})$$

In reality, the quantity that was really desired was the worth of the cell when it was physically removed from the reactor, i.e.,

$$\begin{aligned}\Delta\rho_{w/o\ extension}^{cell} &= \rho(\text{cell in}) - \rho(\text{cell removed}) \\ &= \Delta\rho_{w/extension}^{cell} - \Delta\rho^{extension} \\ \therefore \Delta\rho^{extension} &= \Delta\rho_{w/extension}^{cell} - \Delta\rho_{w/o\ extension}^{cell}\end{aligned}$$

At room temperature and with an air atmosphere it was possible to measure $\Delta\rho^{extension}$ with relative ease. Measurements were also made in nitrogen at temperatures up to 300°C by removing the central cell through the rear face. Additional information on $\Delta\rho^{extension}$ may be inferred from the single HTGR block measurements for which the extension effect is absent. All of these measurements indicate that there is no trend with temperature, although the uncertainties are large. Results of single block measurements in two

previous HTGR experiments⁽¹¹⁾ were also consistent with the assumption of a constant extension effect. The value used for $\Delta\rho^{\text{extension}}$ was taken as the average of the directly measured values (single cell data were not used). The resultant average value for the extension effect is $0.37 \pm 0.11\%$.

5. Central Cell End Cap Correction

Due to the construction of the central cell fuel blocks, there were graphite end pieces at each end of the four block central cell, i.e., the axial fueled dimension for these blocks is $\sim 22\text{-}1/4$ inches versus an overall block length of ~ 24 inches. In fact, all test core blocks have this same feature, i.e., graphite end caps. The presence of this graphite at the ends of the central cell blocks causes flux peaking, which, in turn, leads to a higher value for $\Delta\rho^{\text{cell}}$ than one would observe if no end caps were present.

Dummy end caps were fabricated of graphite and placed in the cavity and their worth was directly measured at room temperature, and with an air atmosphere. The worth of the end caps at elevated temperatures was taken as proportional to the graphite worth measured in the void using the graphite carrier. Since there was some scatter in the measured carrier reactivities, a smoothed set of values were used to evaluate this correction. These values are presented in Table III.

B. Flux Perturbation In the Vicinity of Foils

The relative reaction rates in central cell components and the copper absorber in the cavity were determined, at room temperature only, by foil activation methods. The presence of any given type foil in the lattice perturbs the neutron flux in the vicinity of the foil such that the activity indicated by the foil data is not truly representative of the flux in the unperturbed medium. To correct the foil data to yield results related to fluxes present in the unperturbed medium, two dimensional, two group transport theory calculations were performed using DOT.⁽¹²⁾ Computational models included both bare and cadmium covered foil packets in the $^{233}\text{UO}_2 - ^{232}\text{ThO}_2 - \text{C}$ fuel material and a reference model consisting of the unperturbed medium. Similarly, a model was used which depicted the foils in an all graphite medium, typical of the location used for the monitor foils near the edge of the HTLTR. The two group cross sections required for these calculations were generated by the GRANIT,⁽⁶⁾ BRT-I,⁽⁷⁾ and EGGNIT⁽⁹⁾ codes.

The calculated two group flux perturbations in the foil regions of the $^{233}\text{UO}_2 - ^{232}\text{ThO}_2 - \text{C}$ fuel channel and the foils in the monitor region were used to correct the measured foil activities so as to deduce the foil activity ratios, e.g.,

$$\frac{(SA_o^{(U,Th)O_2 \text{ Foil}})_{\text{Fuel Sub-Cd}}}{(SA_o^{(U,Th)O_2 \text{ Foil}})_{\text{Monitor Sub-Cd}}} = \frac{\bar{\phi}_2^{\text{Fuel}} (\bar{\sigma}_f^{233U})_2^{\text{particles in fuel}}}{\bar{\phi}_2^{\text{Monitor}} (\bar{\sigma}_f^{233U})_2^{\text{particles at monitor}}}$$

that would be characteristic of the unperturbed medium.

Then this value can be used to infer a flux and spectrum

averaged absorption cross section relative to a common

thermal flux at the monitor location, i.e.,

$$\frac{(\sigma_{a_2} \bar{\phi}_2)^{\text{ith component}}}{(\phi_o)_{\text{monitor}}}$$

Finally, the relative reaction rates can be obtained from:

$$\left[\frac{(\sigma_{a_2} \bar{\phi}_2)^i}{(\phi_o)_{\text{monitor}}} N^i V^i \right] = \frac{(\sum_a V \phi)_2^i}{\phi_o^{\text{Monitor}}}$$

C. Experimental Uncertainties

The uncertainty associated with the measured reactivity ratio, $\frac{\Delta\rho_{\text{cell}}}{\Delta\rho_{\text{abs}}}(T)$, is due to the estimated accuracy of the individual reactivity measurements leading to each corrected $\Delta\rho(T)$ value, as footnoted in Table III.

The error associated with $k_{\text{UNCORR}}^{\text{EXP}}$ is the result of propagating the error associated with the measured or calculated quantities used in Equation (1), (2), and (3). For the calculated parameters, errors were assumed as follows:

flux values from 2 DB	$\pm 1\%$
$\sigma_a(T)_2^{\text{Cu}}$	± 0.1 barn
$\Sigma_a(T)_2^{\text{cell}}$	$\pm 3\%$
$Rl_{\text{eff}}^{\text{Cu}}(T)$	± 0.1 barn

The error associated with k_{∞}' is the result of propagating the error due to $k_{\text{UNCORR}}^{\text{EXP}}$ and the calculated correction terms f_1 , f_2 , and g . For the calculated values, errors were assumed as follows:

τ	$\pm 10\%$
B^2	$\pm 20\%$
L^2	$\pm 10\%$
$1-p$	$\pm 10\%$
η_1^f	$\pm 10\%$
$\Sigma_{1 \rightarrow 2}$	$\pm 10\%$
Σ_1^a	$\pm 10\%$
Σ_2^a	$\pm 3\%$
$\nu_{1\Sigma_1}^f$	$\pm 10\%$
$\nu_{2\Sigma_2}^f$	$\pm 10\%$
Flux values from 2 DB	$\pm 1\%$

The quoted uncertainties are at the 67% confidence level.

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