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MEASUREMENT OF PHYSICS
PARAMETERS FOR A MSBR
LATTICE IN THE HTLTR

JANUARY 1972

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E. P. Lippincott

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ABSTRACT

Measurements have been made in the HTLTR on a Thorium-²³³U lattice designed to obtain neutronic parameters needed in the Molten Salt Breeder Reactor program. Measurements were made from 20 to 1000°C and included k_{∞} for the base lattice and reactivity perturbations of a number of samples. The change of k_{∞} with temperature was observed to be smaller than had been predicted by calculation, in qualitative agreement with experimental results from two previous ²³³U lattices in the HTGR Series.

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MEASUREMENT OF PHYSICS PARAMETERS FOR A MSBR LATTICE IN THE HTLTR

E. P. Lippincott

I. INTRODUCTION

The Molten Salt Breeder Reactor (MSBR), a reactor concept which utilizes a fluid fuel with a graphite moderator, is currently being designed by Oak Ridge National Laboratory (ORNL).⁽¹⁾ In cooperation with ORNL, an experiment to measure nuclear data necessary in the design of a MSBR has been completed in the High Temperature Lattice Test Reactor (HTLTR).⁽²⁾ The experiment used a lattice which did not contain molten salt fuel as such, but rather contained a mock-up fuel mixture similar to that used in the High Temperature Gas-Cooled Reactor (HTGR) experiments in the HTLTR.⁽³⁾ To obtain measurements of the effects of the components of the molten salt fuel and the effect of density change in the molten salt, perturbation measurements were carried out on small samples. Perturbation measurements were also made to determine the effects of various geometries of fuel and moderator and to evaluate safety rod strengths.

The HTLTR measurements were made at four temperatures: 20°C, 300°C, 627°C, and 1000°C. The measurements at 627°C provide information at the MSBR design operating temperature. Information at other temperatures indicates behavior as a function of temperature.

II. PRINCIPLE OF THE MEASUREMENT

The principal result of the HTLTR experiments is the determination of the infinite medium neutron multiplication factor, k_{∞} , as a function of temperature.⁽²⁾ 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*

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

* k_{∞} as defined here is equivalent to k_{∞}^+ as defined in Reference 2 and k_{∞}' as defined in Reference 5. The fluxes, ϕ_1 , ϕ_2 , in this paper are equivalent to ϕ_1' , ϕ_2' as defined in References 2 and 5. The primes have been deleted herein for simplicity of notation.

In the two energy group approximation, this becomes

$$k_{\infty} = \frac{v_1 \Sigma_1^f \phi_1 + v_2 \Sigma_2^f \phi_2}{\Sigma_1^a \phi_1 + \Sigma_2^a \phi_2} \quad (2)$$

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

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

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

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.⁽⁴⁾ 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 produced when 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,⁽⁴⁾ and Equations (2) and (3) above, the following relationship between k_{∞} and the measured quantities may be derived,^(5,6)

$$\begin{aligned}
k_{\infty} = 1 - \frac{\Delta\rho^{\text{cell}}}{\Delta\rho^{\text{p}}} \frac{(\Sigma_2^{\text{p}} \phi_2^{\text{p}})}{(\Sigma_2^{\text{a}} \phi_2)_{\text{cell}}} (1 + \alpha) - \frac{(1 + \tau B^2)(1 + L^2 B^2)(1 - p) L^2 B^2}{1 + (1 - p) L^2 B^2} \\
+ \frac{\tau B^2 (1 + L^2 B^2) [\tau B^2 - \eta_1 f_1 (1 - p)]}{1 + \tau B^2 - \eta_1 f_1 (1 - p)} - \frac{\tau B^2 (1 + L^2 B^2)}{1 + \tau B^2 - \eta_1 f_1 (1 - p)} \left(\frac{\Delta\phi}{\phi} + \frac{\Delta\phi^+}{\phi^+} \right) \\
+ \frac{(1 + L^2 B^2) [1 - \eta_1 f_1 (1 - p)]}{1 + \tau B^2 - \eta_1 f_1 (1 - p)} \frac{\Delta\phi}{\phi} \frac{\Delta\phi^+}{\phi^+} \quad (4)
\end{aligned}$$

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. $(\Sigma_2^{\text{a}} \phi_2)$ represents the actual thermal neutron absorptions in the central cell. The quantity α is a correction for the epithermal absorptions in the copper and is given by:

$$\alpha = \frac{\phi_1^+ \Sigma_1^{\text{Cu}} \phi_1}{\phi_2^+ \Sigma_2^{\text{Cu}} \phi_2} \quad (5)$$

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 inserted. 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:

$$\tau = \frac{D_1}{\Sigma_1^{\text{a}} + \Sigma_{12}} \quad (6)$$

$$L^2 = \frac{D_2}{\Sigma_2} \quad (7)$$

$$\eta_1 f_1 = \frac{\nu \Sigma_1^{\text{f}}}{\Sigma_1^{\text{a}}} \quad (8)$$

$$p = \frac{\Sigma_{12}}{\Sigma_{12} + \Sigma_1^{\text{a}}} \quad (9)$$

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

$$k_{\infty} = \frac{(1 + \tau B^2)(1 + L^2 B^2)}{1 + (1-p)L^2 B^2} \quad (10)$$

Since the buckling is not measured experimentally and cannot be calculated to the desired accuracy, Equation (10) is used to eliminate B^2 from Equation (4). Equation (4) may be written as

$$k_{\infty} - 1 = A - a_1 B^2 - a_2 B^4 \quad (11)$$

to second order in B^2 , where

$$A = - \frac{\Delta \rho^{ce11}}{\Delta \rho^p} \frac{(\Sigma_2 \phi_2 V)^p}{(\Sigma_2 \phi_2 V)^{ce11}} (1 + \alpha) + \frac{\Delta \Phi}{\Phi} \frac{\Delta \Phi^+}{\Phi^+} \quad (12)$$

$$a_1 = L^2 (1-p) + \frac{\tau \eta_1 f_1 (1-p)}{1 - \eta_1 f_1 (1-p)} + \frac{\tau}{1 - \eta_1 f_1 (1-p)} \left(\frac{\Delta \Phi}{\Phi} + \frac{\Delta \Phi^+}{\Phi^+} \right) - \frac{L^2 [1 - \eta_1 f_1 (1-p)]}{1 - \eta_1 f_1 (1-p)} - \tau \frac{\Delta \Phi}{\Phi} \frac{\Delta \Phi^+}{\Phi^+} \quad (13)$$

$$a_2 = (1-p)L^2(\tau + pL^2) - \frac{\tau}{1 - \eta_1 f_1 (1-p)} \left[\frac{\tau}{1 - \eta_1 f_1 (1-p)} - L^2 \eta_1 f_1 (1-p) \right] + \frac{\tau L^2 [1 - \eta_1 f_1 (1-p)]}{[1 - \eta_1 f_1 (1-p)]^2} - \tau^2 \left(\frac{\Delta \Phi}{\Phi} + \frac{\Delta \Phi^+}{\Phi^+} + \frac{\Delta \Phi}{\Phi} \frac{\Delta \Phi^+}{\Phi^+} \right). \quad (14)$$

Solving for B^2 to second order from Equation (10), substituting in (11) and inverting the series to solve for $k_{\infty} - 1$ results in:

$$k_{\infty} - 1 = b_1 A + b_2 A^2 \quad (15)$$

where

$$b_1 = \frac{\tau + pL^2}{a_1 + \tau + pL^2} \quad (16)$$

and

$$b_2 = \frac{-a_2(\tau + pL^2) + a_1 pL^2 [\tau - L^2(1-p)]}{(\tau + pL^2 + a_1)^3} \quad (17)$$

III. DESCRIPTION OF LATTICE

A. Standard Fuel Blocks

The mock-up MSBR lattice is composed of graphite blocks 3 3/4 inch square by four feet long, each containing four 0.786-inch diameter longitudinal fuel channels.

The graphite blocks were made from SGBF graphite and have an absorption cross section of 3.80 millibarns. Each block contains four fuel channels on a pitch of 1 7/8 inches and each channel was drilled to 0.786 ± 0.001 inches in diameter. The fuel channels are filled with a mixture of graphite particles, ThO_2 particles, and ThO_2 - $^{233}\text{UO}_2$ microspheres coated with pyrocarbon. Blocks were constructed in lengths of four feet and one foot and the central cell was two feet long. Each fuel channel was sealed with 0.5-inch long graphite end plugs on each end. A diagram of the lattice loaded into the HTLTR is shown in Figure 1.

The fuel blocks were loaded by putting a measured amount of fuel blend in each channel and vibrating. If volume remained, extra fuel mix was added to fill the channel. In this way a nearly uniform loading was achieved.

The ThO_2 - $^{233}\text{UO}_2$ microspheres were made at ORNL. The mean microsphere diameter for the particles used in the central cell was $300\mu\text{m}$ with a standard deviation of $30\mu\text{m}$. Each microsphere was nominally composed of 3 parts ThO_2 and 1 part UO_2 (97.5% ^{233}U). The microspheres were coated with approximately $100\mu\text{m}$ of pyrocarbon. A detailed description and analysis of the microspheres is given in Appendix B.

The amounts of ^{233}U and Th in each batch of particles were 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 ThO_2 used in the fuel mix was in the form of uncoated irregularly shaped particles. The size distribution as given in Table I was measured by screening. Since the particles are irregularly shaped, this distribution

FIGURE 1. MSBR Core (Central Region of HTLTR Core)

only approximates the effective particle diameters. The ThO_2 particles are assumed to have a density of 9.86 g/cm^3 .

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 $210\mu\text{m}$ (-65 mesh) and the other half were $350\mu\text{m}$ to $590\mu\text{m}$ (-28 mesh + 42 mesh). It was observed that the graphite particles were shaped like flakes which accounts for the relatively low packing density of the fuel and for the care that was necessary to get uniform fuel loadings. The uniformity of the fuel loadings was checked using x-radiography.

TABLE I
THORIA PARTICLE SIZE DISTRIBUTION*

<u>Screen Size</u>	<u>Particle Size Range (μm)</u>	<u>Weight Percent</u>
+65	>210	4.4
100-65	149-210	14.2
150-100	105-149	17.2
200-150	74-105	14.4
325-200	44-74	32.2
-325	0-44	17.6

* Measured on Batch used in Central Cell

Special care was taken with the central cell to ensure a uniform loading. The composition of the central cell is shown in Table II. Including the end gap graphite, the C/Th atom ratio for the central cell is 152.5 and the $\text{C}/^{233}\text{U}$ ratio is 9911. If the end caps are not included these ratios are 146.1 and 9493, respectively.

TABLE II
COMPOSITION OF CENTRAL CELL

<u>Component</u>	<u>Grams of Element</u>	<u>Atoms/Barn-cm (Each Region)</u>
Moderator Region Including End Caps (V = 19,200 cm ³)		
C	30632	0.08004
N*	6.72	1.50 x 10 ⁻⁵
Fuel Region (V = 2926.6 cm ³)		
C	2260.	0.03874
N*	1.24	2.56 x 10 ⁻⁵
O	583.9	0.00750
²³² Th	4169.	0.003696
²³³ U	64.45	5.689 x 10 ⁻⁵
²³⁴ U	0.692	6.08 x 10 ⁻⁷
²³⁵ U	0.0608	5.32 x 10 ⁻⁸
²³⁶ U	0.0046	4.0 x 10 ⁻⁹
²³⁸ U	0.935	8.08 x 10 ⁻⁷

* Amount at 20°C in N₂ atmosphere. The nitrogen density was taken proportional to 1/T at elevated temperatures. Density changes in other cell components were assumed to be negligible.

B. Perturbation Samples

Special blocks and samples were constructed to measure various perturbations necessary in obtaining k_{∞} and correlating the result with the actual MSBR design. These samples are listed in Table III.

TABLE III
MSBR PERTURBATION SAMPLES

Standard Lattice Central Cell	
Copper	
Graphite Carrier for Copper	
V_2O_5 Cell	
Increased Fuel Density Cell	
Four Hole Cell, 1 9/16-inch Diameter	
Four Hole Cell, 2 37/64-inch Diameter	
Solid Graphite Block	
Hastelloy Block	
Single Hole Cell - 4-inch Diameter	
Single Hole Cell - 6-inch Diameter	
Cruciform Cell with Material Worth Samples:	
Graphite	^{233}U
Copper	^{235}U
Beryllium	^{239}Pu
Lithium	Hastelloy-N
Fluorine	^{233}U -Th-C Fuel Mixture
Thorium	

To measure k_{∞} it is necessary to measure the reactivity worths of the standard central cell and copper poison. The copper poison was inserted on a graphite carrier. Two 3-inch x 24-inch pieces of 0.010-inch copper foil were placed flat, side by side, on the carrier. Two carriers were used, one to hold the copper and an identical one to measure the carrier worth without the copper. The original graphite carriers weighed 1120 grams but were found to be too fragile. A heavier duty model was constructed and used at 300°C and above. This latter carrier weighed 2040 grams. No difference in worth per gram for the copper or carrier was observed when this change was made.

In addition to the standard central cell, various perturbed central cells were constructed. These cells are described in Table IV and shown in Figure 2. Three cells are as shown in Figure 2a: the standard cell, a cell with V_2O_3 in place of the ThO_2 to determine the thorium resonance integral, and an increased density cell for the density coefficient. The cells in Figure 2b and 2f have the same volume of fuel as the standard cell and provide information on fuel geometry effects. Other effects of geometry with different amounts of fuel are measured by cells illustrated in Figure 2c, d and e.

To measure effects of control materials a graphite block (Figure 2g) and hastelloy block (Figure 2h) were used. The graphite block was a solid block the size of the central cell and weighed 35.64 kg. The hastelloy block was also graphite, but had slots for insertion of one to four hastelloy bars. When all four bars are inserted, the hastelloy forms a cross. Each hastelloy piece was approximately $22\frac{1}{2} \times 2\frac{1}{2} \times \frac{1}{4}$ inch and the pieces weighed 2073.7, 2105.1, 2124.1 and 2134.9 gm, respectively.

The cruciform block (Figure 2f) is also used in the material worth measurements. For these measurements, the graphite cylinder in the sample position is removed and a 2-inch ID*, 2.75-inch OD graphite tube containing the material to be measured is inserted. The amount of material contained in each of the material worth samples is shown in Table V, together with the amount of graphite in the sample (including the tube and end caps). In the case of the samples of pyrocarbon-coated fuel particles and ThO_2 , the remaining volume is made up of graphite powder.

* With the exception of the 7LiF sample which was 1.375-inch ID.

A. STANDARD

B. 1-9/16" DIA

C. 2-37/64" DIA

D. 4" DIA

E. 6" DIA

F. CRUCIFORM

G. SOLID GRAPHITE

H. HASTELLOY BLOCK

FIGURE 2. 7 1/2 in. x 7 1/2 in x 24 in. Central Cells

The ThO_2 - $^{233}\text{UO}_2$ fuel particles are identical to the ones used in the standard blocks, the $^{235}\text{UC}_2$ particles are the same as used in the initial HTGR experiment,⁽²⁾ and the ZrO_2 - $^{239}\text{PuO}_2$ particles are a special sample of PuO_2 diluted with ZrO_2 . Further description of these particles is given in Appendix B. The remaining tubes are completely filled with the material except for the samples of copper and hastelloy foil, which contain an inner cylinder of graphite holding the foil to the 1-inch radius and essentially filling the entire tube. The total graphite for the fuel mix tube includes 925.6 gm of graphite powder in the fuel blend.

TABLE IV
TEST CELL DESCRIPTION

<u>Cell</u>	<u>Block Graphite-gm (including end caps)</u>	<u>Fuel Mixture-gm.*</u>
Standard	30632.	7079.
V_2O_3	30699.	4036.
Increased Fuel Density	30540.	7685.
Four Hole - 1 9/16 dia.	30161.	7450.
Four Hole - 2 37/64 dia.	22960.	19084.
Single Hole - 4-inch dia.	28686.	11487.
Single Hole - 6-inch dia.	18312.	25845.
Cruciform Block	31027.	7011.
Graphite Block	35635.	--
Hastelloy Block	32914.	--

*The fuel mixture for each test cell is identical to that used in the standard block except for the V_2O_3 cell. The V_2O_3 mixture is made up of 1725 gm of V_2O_3 and pyrocarbon-coated fuel particles containing 58.65 gm of ^{233}U , 171.33 gm of ^{232}Th , and 17 gm of ^{16}O , and the remainder of the UO36 gm is graphite.

TABLE V
COMPOSITION OF MATERIAL WORTH SAMPLES

<u>Sample Number</u>	<u>Material</u>	<u>Gm. of Material</u>	<u>Gm. of Graphite</u>
1	Solid Graphite	3764.1	3764.1
2	Graphite Powder	1223.8	3054.1
3	Void	-	1919.5
4	Copper Foil (0.010-inch thick)	197.1	3740.9
5	Beryllium Rod	2011.6	1847.6
6	Teflon Rod (CF ₂)	2117.6	1875.3
7	⁷ LiF (78ppm ⁶ Li)	1311.4	2920.3
8	ThO ₂	250.0	3044.0
9	ThO ₂ - ²³³ UO ₂ : UO ₂ (97.5% ²³³ UO ₂)	8.75	3134.9
	ThO ₂	25.0	
10	²³⁵ UC ₂ : U (93% ²³⁵ U)	11.36	3110.2
11	ZrO ₂ - ²³⁹ PuO ₂ : PuO ₂ (98% ²³⁹ Pu)	5.32	3164.1
	ZrO ₂	70.36	
12	Hastelloy Foil (0.011-inch thick)	186.4	3703.4
13	Fuel Mix: ThO ₂ -UO ₂ (97.5% ²³³ UO ₂)	30.78	2763.7
	ThO ₂	1941.8	

C. HTLTR Fuel Loading

The HTLTR fuel loading diagram is shown in Figure 3. In this figure the MSBR core is loaded in the center and the fuel shims surrounding the MSBR section are shown. No space actually exists between the test core (lettered horizontal coordinates) and the main stack (numbered horizontal coordinates). Only the adjacent portion of the main stack is shown. Located one ring removed from the horizontal control rods are fuel push columns⁽⁷⁾ used to add reactivity to make up for loss in reactivity with temperature change. No other changes in loading were made.

The loading shown in Figure 3 gave a reasonably good flux match (see the following section). Therefore this was the only loading used in the MSBR experiment.

- 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 3. HTLTR Fuel Loading Diagram - MSBR Experiment

IV. EXPERIMENTAL MEASUREMENTS

A. Flux Matching

In order to measure the degree of flux mismatch, radial and axial traverses were made using bare and cadmium-covered gold foils. The axial traverse indicated a good match when perturbations due to the end caps are considered. The radial variation of the gold cadmium ratio is shown in Figure 4. It is seen that the spectrum is slightly too thermal since the cadmium ratio rises as the edge of the MSBR region is approached. However, in the central cell region the cadmium ratio is constant to within 1%.

The solid curve in Figure 4 is a calculation of ϕ_1/ϕ_2 (normalized at $R = 10$ cm.) using the two dimensional diffusion theory code, 2DB.⁽⁸⁾ Excellent agreement with this calculation is observed, which indicates that the 2DB calculations may be used to provide a reasonable estimate of the flux mismatch.

B. Measurement of Reaction Rates

The measurement of relative thermal reaction rates in the actual cell and copper absorber is carried out at room temperature using foils. These foils are normalized to foils placed on a rotator at a location near the edge of the HTLTR. The rotator ensures that each type of foil sees an identical flux.

The reaction rate in the copper poison was measured by placing the poison strips in the cavity left when the central cell was removed and irradiating the material. Foils were punched from selected locations in the strips and the copper activity determined, to obtain the integral of absorptions in the poison strips.

The cell reaction rate was measured using 0.005-inch copper foils to evaluate $1/v$ absorptions and fuel foils to evaluate fuel absorption. The copper foils were placed axially and radially between the central cell blocks to allow an integral of the flux over the cell to be calculated.

Three fuel channels were modified to allow foils to be inserted. These channels contained fuel in graphite cylinders having the same inner diameter

FIGURE 4. Radial Gold Cadmium Ratio Traverse

as the standard fuel channel. Three of the cylinders occupied one fuel channel which thereby allowed foils to be placed in two interior positions. The ends of the fuel cylinders were sealed with 0.010-inch aluminum and thus the bare foils were separated from the fuel itself by 0.010-inch and the cadmium-covered foils were separated by 0.050-inches (including the cover). The three channels containing foils were arranged so that all 16 channels in the central cell could be evaluated using rotational symmetry.

Foils irradiated in the fuel channels were fuel foils, thorium foils, and copper foils. The copper foils were used to evaluate the $1/v$ absorptions in the graphite and minor constituents of the fuel. Deviation of ^{235}U from a $1/v$ absorber was calculated using GRANIT.⁽⁹⁾

The ^{233}U absorptions were evaluated using the (n,f) reaction in the fuel foil. These foils consisted of a carefully measured portion of the fuel blend about 0.1 inches thick. The difference in α for ^{233}U between the central cell and the monitor location was calculated to be negligible. The relative fission rate may therefore be used as a measure of the relative absorption rate.

The thorium results were evaluated both from the fuel foils and from separate thorium foils. The latter measurement gave an anomalously low result. The absorptions evaluated using the fuel foils were slightly above the $1/v$ reaction rate. However, larger errors were present in the thorium evaluation due to the unknown effect of epithermal absorptions in the monitor foil (estimated to be about 10%). The value calculated by GRANIT showed thorium to be $1/v$. Since the fuel foil result agreed within error with the $1/v$ reaction rate, the latter was used.

In order to evaluate relative thermal absorptions, both bare and cadmium-covered (0.040-inch thick cadmium) foils are irradiated. The measured relative reaction rates must then be corrected for the perturbations caused by the foils and cadmium covers.⁽¹⁰⁾ These corrections were calculated using the two-dimensional transport theory code DOTSN.⁽¹¹⁾ The corrections to the bare activity were small (about 0.2% or less). The corrections for the cadmium cover perturbations were larger, however. These perturbations arise from depression of the epithermal flux in the vicinity due to thermal absorption in the cadmium, epithermal absorption in the cadmium, and due to

production of thermal neutrons by scattering inside the cadmium cover. The DOTSN calculation provides the thermal and epithermal flux inside the cadmium cover relative to the unperturbed flux far from the foil. Using the DOTSN results, the thermal and epithermal flux are found by the relations:

$$A_2 = 1.008 A^{\text{bare}} - 1.060 A^{\text{Cd}} \quad (18a)$$

$$A_1 = 0.008 A^{\text{bare}} + 1.060 A^{\text{Cd}} \quad (18b)$$

It was also necessary to correct for the epithermal absorption in the monitor foil. This effect was calculated to decrease the monitor absorptions by 0.9% for both 0.005 and 0.010-inch copper and by 1.8% for the ^{233}U fuel foils. These factors were derived from measured copper and gold cadmium ratios at the monitor location.

Thermal cross sections at the monitor location were evaluated using a spectrum from a THERMOS⁽¹²⁾ calculation of the HTLTR. The cross section for 0.010-inch copper was obtained using a thermal disadvantage factor of 1.1%.⁽¹³⁾ The cross sections of the materials in the ^{233}U particle were calculated using an averaging routine CROSAV⁽¹⁴⁾ which uses a collision probability routine together with the THERMOS fluxes and cross sections from the THERMOS BNW master library to calculate effective cross sections in the particle.

The absorptions in the copper poison and central cell are summarized in Table VI. The errors shown in the relative absorptions (column 5) include uncertainties in the grams of material in the central cell (column 1), uncertainties in the cross section (column 3) (evaluated at the monitor location and normalized to $1/v$ at 2200 m/sec.), and uncertainties in the activity (central cell absorptions/gram normalized to monitor absorptions/gram). Since these errors are to some extent systematic, the error in the total cell absorption has been taken to be the sum of the errors in the absorption in each cell component. Otherwise, it is felt that this error would be unrealistically small. The central cell reaction rate normalized to the thermal reaction rate in one gram of copper is then found from Table VI to be 4836 ± 104 .

TABLE VI
EVALUATION OF RELATIVE REACTION RATES

Component	Weight (gm)	Atomic Weight	σ Monitor	Relative Activity	Relative Absorption Rate
<u>Cell out-Cu.</u>					
Thermal Epithermal	1.0	63.54	3.75 (0.010-inch)	1.138 0.1530	0.0672 $\pm$ 0.0010
<u>Cell in</u>					
<u>Moderator Region</u>					
C	29245	12.0	3.80-03	1.138	10.54 $\pm$ 0.17
N	6.42	14.0	1.85	1.138	0.97 $\pm$ 0.02
<u>Fuel Region</u>					
<u>Particles</u>					
²³³ U	64.45	233.0	552.7	1.100	168.17 $\pm$ 2.38
²³² U	189.0	232.0	7.101	1.083	6.27 $\pm$ 0.12
²³⁴ U	0.692	234.0	91.3	1.083	0.29 $\pm$ 0.01
²³⁵ U	0.0608	235.0	623.0	1.064	0.17
²³⁸ U	0.935	238.0	2.63	1.087	0.01
¹⁶ O	34.9	16.0	1.71-04	1.083	0.00
<u>ThO₂</u>					
²³² Th	3980.	232.0	7.401	1.083	137.50 $\pm$ 2.31
¹⁶ O	549.0	16.0	1.78-04	1.083	0.01
<u>Graphite</u>					
C	2260	12.0	3.80-03	1.083	0.78 $\pm$ 0.01
N	1.74	14.0	1.85	1.083	0.25
<u>Total Cell</u>					325.0 $\pm$ 5.0

C. Measurement of Reactivities

Reactivity measurements were made by placing a sample in the void and measuring the change in reactor asymptotic period. The change in reactivity was then calculated using the inhour equation.⁽¹⁵⁾ A correction for the reactivity of the nitrogen in the void was calculated from the worth of copper in the void.⁽¹⁶⁾ This correction for the 7 1/2 x 7 1/2 x 24 inch cells and the corrected reactivity worths for the various central cells, copper, and hastelloy, are summarized in Table VII. No correction for end caps on the central cell is included in Table VII. The reactivity worth of copper and graphite are given in ϕ /gm. The copper worth was measured by inserting two 0.010 inch copper foils on the graphite carrier. The worth of the hastelloy block (graphite) was measured empty and with one hastelloy piece at each temperature, and with additional hastelloy pieces at room temperature and 627°C.

The MSBR experiment was the first to utilize the new sample changer. This device allows samples to be preheated before insertion in the reactor and thus enables temperature transients during sample changes to be minimized. This results in a time saving during reactivity measurements and an improvement in accuracy. Errors have not been included in Table VII, but typical errors might be $\pm 0.02\phi$ at room temperature, $\pm 0.04\phi$ at 300°C, and 627°C, and $\pm 0.07\phi$ at 1000°C. Since samples could not be preheated to 1000°C, some temperature transients remained at this temperature and the accuracy is therefore lower. These errors are estimated from the consistency of the data and represent approximately one standard deviation. A second advantage of the sample changer is the elimination of the extension effect which created an uncertainty in earlier experiments.

Additional measurements were made at room temperature in air. These measurements included a measurement of the copper worth on the carrier versus the copper worth in the void and the worth of an amount of graphite equivalent to the end cap region on the central cell. Within error the effect of the carrier graphite on the copper worth was found to be zero. The end cap worth was measured to be 0.60 ϕ .

The material worth measurements were made by inserting sample tubes in the cruciform block. The results of these measurements relative to the

TABLE VII

REACTIVITY MEASUREMENTS (CORRECTED FOR N₂ IN VOIDS)

	20°C	300°C	627°C	1000°C
N ₂ Correction	-0.98¢	-0.49¢	-0.31¢	-0.21¢
Standard Central Cell	3.28¢	1.91¢	1.39¢	1.24¢
Copper	0.0173¢/gm	0.0174¢/gm	0.0170¢/gm	0.0169¢/gm
Graphite Carrier	0.39 x 10 ⁻³ ¢/gm	0.47 x 10 ⁻³ ¢/gm	0.50 x 10 ⁻³ ¢/gm	0.56 x 10 ⁻³ ¢/gm
V ₂ O ₃ Cell	22.05¢	21.79¢	22.12¢	22.68¢
Increased Density Cell	4.75¢	3.02¢	2.17¢	1.92¢
4-hole cell (1-4/16 diameter)	6.84¢	5.68¢	5.32¢	5.38¢
4-hole cell (2-37/64 diameter)	0.62¢	-3.94¢	-7.48¢	-9.68¢
Single Hole Cell (4-inches)	8.04¢	6.06¢	4.90¢	4.38¢
Single Hole Cell (6-inches)	-2.50¢	-7.83¢	-11.90¢	-14.60¢
Cruciform Block	4.07¢	2.33¢	1.28¢	0.93¢
Graphite Block	12.35¢	14.46¢	16.74¢	18.54¢
Empty Hastelloy Block	11.61¢	13.73¢	15.66¢	17.32¢
Block + One Hastelloy Piece	-24.63¢	-22.74¢	-21.00¢	-19.13¢
Block + Two Hastelloy Pieces				
Adjacent Positions	-53.06¢		-50.31¢	
Opposite Positions	-54.65¢			
Block + Three Hastelloy Pieces	-76.8¢			
Block + Four Hastelloy Pieces	-95.8¢		-99.2¢	

cruciform block with the solid graphite sample are presented in Table VIII. The graphite powder sample was measured only at room temperature since data from this sample was consistent with the graphite worth obtained from the solid graphite sample versus the void. Other samples were measured at each temperature except where material properties limited the samples to less than 1000°C.

The measured graphite worth was used to correct the samples to worth relative to a void. The corrected values are presented in Table IX. In cases where the sample did not completely fill the volume, a small nitrogen correction was also made. The graphite worth includes the N_2 in the pores of the graphite.

Worths of various materials and isotopes may be derived from Table IX and are given in Table X in ¢/kg. The estimated errors in the final numbers are also presented. By using measured or estimated worths for other isotopes present, values for worths of individual isotopes are derived. The worth of the actual lithium used is presented together with an estimated worth for pure ^7Li . The worths derived for ^{233}U and Pu (98% ^{239}Pu) and the ^{235}U worth are presented with no correction for flux depression in the particles or in the fuel tube.

TABLE VIII

MATERIAL WORTH MEASUREMENTS (CENTS) (UNCORRECTED)

	<u>Sample</u>	<u>20°C</u>	<u>300°C</u>	<u>627°C</u>	<u>1000°C</u>
1	Solid Graphite (Standard)	0	0	0	0
2	Graphite Powder	-0.29			
3	Void	-0.75	-0.72	-0.82	-0.91
4	Copper Foil	-3.53	-3.38	-3.27	-3.25
5	Beryllium Rod	+0.96	+1.20	+1.35	
6	Teflon Rod (CF ₂)	-0.59	-0.54		
7	⁷ LiF	-2.04	-1.91	-1.92	
8	ThO ₂	-3.80	-3.87	-3.89	-3.89
9	ThO ₂ - ²³³ UO ₂	+4.72	+4.35	+4.07	+3.84
10	²³⁵ UC ₂	+4.36	+3.98	+3.73	+3.30
11	ZrO ₂ - ²³⁹ PuO ₂	+4.04	+4.34	+5.05	+5.40
12	Hastelloy Foil	-3.83	-3.78	-3.60	-3.57
13	Fuel Mix	-1.75	-2.54	-3.30	-3.88

TABLE IX

CORRECTED MATERIAL WORTH MEASUREMENTS (CENTS) (RELATIVE TO VOID)

	<u>20°C</u>	<u>300°C</u>	<u>627°C</u>	<u>1000°C</u>
Graphite (N ₂ atmosphere)	+0.70	+0.69	+0.80	+0.90
Copper	-3.52	-3.37	-3.26	-3.24
Beryllium	+1.69	+1.93	+2.19	---
Teflon (CF ₂)	+0.14	+0.18	---	---
⁷ LiF	-1.72	-1.59	-1.55	---
ThO ₂	-3.51	-3.59	-3.57	-3.53
ThO ₂ - ²³³ UO ₂	+4.98	+4.60	+4.35	+4.15
²³⁵ UC ₂ (93%)	+4.63	+4.24	+4.02	+3.62
ZrO ₂ - ²³⁹ Pu	+4.28	+4.57	+5.32	+5.70
Hastelloy	-3.81	-3.76	-3.58	-3.53
Fuel Mix	-0.96	-1.79	-2.44	-2.91

TABLE X
MATERIAL WORTHS (ϵ /kg)

	20°C	300°C	627°C	1000°C
Graphite (N ₂ atmosphere)	0.38 ± 0.01	0.37 ± 0.02	0.43 ± 0.02	0.49 ± 0.04
¹² C	0.39 ± 0.01	0.38 ± 0.02	0.44 ± 0.02	0.49 ± 0.04
F	-0.03 ± 0.02	-0.01 ± 0.04	---	---
⁷ Li (78 ppm ⁶ Li)	-4.75 ± 0.05	-4.47 ± 0.11	-4.35 ± 0.11	---
⁷ Li (estimated)	-1.84 ± 0.18	-1.58 ± 0.19	-1.55 ± 0.19	---
Be	+0.84 ± 0.01	+0.96 ± 0.02	+1.09 ± 0.02	---
Cu	-17.9 ± 0.1	-17.1 ± 0.2	-16.5 ± 0.2	-16.4 ± 0.3
Hastelloy	-20.4 ± 0.1	-20.2 ± 0.2	-19.2 ± 0.2	-18.9 ± 0.4
ThO ₂	-14.0 ± 0.1	-14.4 ± 0.2	-14.3 ± 0.2	-14.1 ± 0.3
Th	-15.9 ± 0.1	-16.3 ± 0.2	-16.2 ± 0.2	-16.0 ± 0.3
ThO ₂ - ²³³ UO ₂ (particles)	147.6 ± 1.0	136.3 ± 1.6	128.9 ± 1.5	123.0 ± 2.9
²³³ U	711 ± 10	661 ± 12	628 ± 11	600 ± 17
²³⁵ U	438 ± 4	401 ± 5	381 ± 5	343 ± 9
ZrO ₂ - ²³⁹ PuO ₂	56.6 ± 0.5	60.4 ± 0.7	70.3 ± 0.9	75.3 ± 1.8
Pu (98% ²³⁹ Pu)	919 ± 13	980 ± 18	1140 ± 20	1215 ± 32
Fuel Mix	-0.33 ± 0.01	-0.62 ± 0.02	-0.84 ± 0.02	-1.00 ± 0.03

V. EVALUATION OF k_{∞}

The value of k_{∞} at each temperature is determined using Equation 15. The evaluation of k_{∞} is summarized in Table XI.

The first step in the evaluation of k_{∞} is the calculation of A given by Equation (12). The measurement of the reactivities of central cell and poison are described in Section IV C. The central cell worth without end caps is obtained by subtracting the end cap worth. This worth was measured only at room temperature and the worth at elevated temperatures was taken proportional to the graphite carrier worth. The reaction rates are obtained from Table VI. The evaluation of the epithermal neutron contribution to the copper worth, α (Equation 5), is obtained from the measured epithermal absorptions in the copper and the calculated worth of epithermal neutrons (see below). A calculation using six groups for the HTGR-2 experiment showed that the two group calculation is adequate.⁽¹⁶⁾ The change in α with temperature was evaluated using EGGNIT⁽¹⁷⁾ and GRANIT.⁽⁹⁾

The calculation of the mismatch correction is summarized in Table XII. Fundamental mode fluxes are determined from Equation (3) and its adjoint. The fundamental mode value is for a homogenized cell without the end caps. The end caps were included in a one dimensional slab calculation using the transport code DTF⁽¹⁸⁾ and two energy groups. The calculation included two regions: the homogenized cell and the end cap region. A third calculation was performed using the two dimensional diffusion theory code 2DB⁽⁸⁾ to calculate the actual reactor fluxes. The 2DB calculation includes the entire HTLTR and uses the same model used in the HTGR analysis.⁽¹⁶⁾ A comparison of the 2DB calculation with the experimental flux traverse was shown in Figure 4. For the adjoint case, the 2DB calculation was carried out for the cell-out case. Since 2DB can not handle a void, an isotropic scatterer was entered in this region. The equivalence of the scatterer to a void was checked using transport theory.⁽¹⁹⁾

Table XII shows that the flux mismatch is nearly constant and is mostly due to the end caps. The adjoint mismatch, however, is not due to the end

cap perturbation and increases with temperature. The effect of the mismatch correction is shown in Table XI where k_{∞} is evaluated both with and without the mismatch terms. The correction is only 0.0015 at room temperature and decreases to 0.0006 at 1000°C.

TABLE XI
EVALUATION OF k_{∞}

	20°	300°	627°	1000°
$\Delta\rho^{\text{cell}}$ (ϕ)	3.28	1.91	1.39	1.24
End cap worth (ϕ)	0.60	0.75	0.82	0.92
$\Delta\rho^{\text{cell}}_{\text{net}}$ (ϕ)	2.68 $\pm$ 0.04	1.16 $\pm$ 0.06	0.57 $\pm$ 0.06	0.32 $\pm$ 0.10
$\Delta\rho^{\text{Cu}}/\text{M}^{\text{Cu}}$ (ϕ/gm)	0.0173 $\pm$ 0.0001	0.0174 $\pm$ 0.0002	0.0170 $\pm$ 0.0002	0.0169 $\pm$ 0.0003
$\Delta\rho^{\text{cell}}/(\Delta\rho^{\text{Cu}}/\text{M}^{\text{Cu}})$ gm	154.9 $\pm$ 2.8	66.7 $\pm$ 4.2	33.5 $\pm$ 4.6	18.9 $\pm$ 6.1
$1 + \alpha$	1.117	1.119	1.121	1.124
$(\Sigma\phi V)^{\text{cell}}/(\Sigma\phi V)^{\text{Cu}}$ gm	4836 $\pm$ 104	4889 $\pm$ 109	4942 $\pm$ 114	5000 $\pm$ 120
A (Equation 12) (no mismatch)	0.0358 $\pm$ 0.0010	0.0153 $\pm$ 0.0010	0.0076 $\pm$ 0.0011	0.0042 $\pm$ 0.0014
A (with mismatch)	0.0364 $\pm$ 0.0012	0.0161 $\pm$ 0.0012	0.0084 $\pm$ 0.0013	0.0049 $\pm$ 0.0015
b_1 (Equation 16) (no mismatch)	0.7584	0.7521	0.7453	0.7377
b_1 (with mismatch)	0.7887	0.7846	0.7740	0.7630
b_2 (Equation 17)	0.31	0.26	0.21	0.17
k_{∞} (no mismatch)	1.0276	1.0116	1.0057	1.0031
k_{∞} (including mismatch)	1.0291 $\pm$ 0.0012	1.0127 $\pm$ 0.0010	1.0065 $\pm$ 0.0010	1.0037 $\pm$ 0.0012

TABLE XII

CALCULATED FLUXES AND ADJOINTS

	20°	300°	627°	1000°
ϕ_1/ϕ_2 Fundamental Mode (no end caps)	1.9706	1.6881	1.4744	1.3136
ϕ_1/ϕ_2 DTF (with end caps)	1.8920			1.2619
ϕ_1/ϕ_2 2-DB (HTLTR)	1.8847	1.6072		1.2640
$\Delta\phi/\phi$	-0.0436	-0.0479	(-0.042)*	-0.0378
ϕ_1^+/ϕ_2^+ Fundamental Mode (no end caps)	0.864	0.854	0.842	0.831
ϕ_1^+/ϕ_2^+ DTF (with end caps)	0.866			0.834
ϕ_1^+/ϕ_2^+ 2-DB (HTLTR) Cell	0.856			0.804
Void	0.853	0.840		0.814
$\Delta\phi^+/\phi^+$	-0.0127	-0.0166	(-0.019)*	-0.0196

* INTERPOLATED

VI. 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:

$$k_{\infty} = \frac{\eta_2 f_2 p + \eta_1 f_1 (1-p) + \eta_1 f_1 (1-p) L^2 B^2}{1 + (1-p) L^2 B^2} \quad (19)$$

The buckling may be evaluated to first order by

$$B^2 = \frac{\eta_1 f_1 (1-p) + \eta_2 f_2 p - 1}{\tau + L^2 [1 - \eta_1 f_1 (1-p)]} \quad (20)$$

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

The computer codes EGGNIT⁽¹⁷⁾ and GRANIT⁽⁹⁾ 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_{∞} . Thermal expansion effects were assumed to be negligible in the calculations at elevated temperatures.

EGGNIT is a modification of GAM⁽²⁰⁾ that uses the Nordheim integration technique⁽²¹⁾ 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.

The thermal region was analyzed using GRANIT, a modification of THERMOS,⁽²²⁾ 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.

		TABLE XIII			
		THEORETICAL PARAMETERS AND k_{∞}			
		20°	300°	627°	1000°
Σ_1^a	cm^{-1}	1.12546×10^{-3}	1.20803×10^{-3}	1.27522×10^{-3}	1.33581×10^{-3}
Σ_{12}	cm^{-1}	2.69043×10^{-3}	2.66012×10^{-3}	2.63161×10^{-3}	2.60646×10^{-3}
τ (Equation 5)	cm^2	318.62	314.50	311.54	308.85
$\eta_1 f_1$ (Equation 7)		0.73632	0.68135	0.64099	0.61119
p (Equation 8)		0.70506	0.68770	0.67359	0.66116
Σ_2^a	cm^{-1}	5.19798×10^{-3}	4.43424×10^{-3}	3.85272×10^{-3}	3.41407×10^{-3}
L^2	cm^2	186.49	218.11	249.42	281.16
$\eta_2 f_2$		1.18084	1.18577	1.19547	1.20753
$\eta_2 f_2 p$		0.83256	0.81545	0.80526	0.79837
$\eta_1 f_1 (1-p)$		0.21717	0.21279	0.20923	0.20710
B^2 (Equation 20)	cm^{-2}	1.0704×10^{-4}	0.5808×10^{-4}	0.2847×10^{-4}	0.1029×10^{-4}
$L^2 B^2$		0.01996	0.01267	0.00710	0.00289
k_{∞} (Equation 19)		1.0479	1.0269	1.0136	1.0051

A comparison of the theoretical and experimental values of k_{∞} plotted versus the square root of the absolute temperature is presented in Figure 5. It may be noted that the experimental curve lies below the predicted k_{∞} at all temperatures and also exhibits a smaller change with temperature. The discrepancy is greatest at room temperature. Even when the effect of loading errors and cross section errors on the theoretical k_{∞} are considered, the difference is greater than the expected error.

The change in the measured k_{∞} from 20°C to 1000°C is -0.0254 ± 0.0017 . This change is significantly less than the calculated change of -0.0428 , and is similar to the comparisons obtained for the two HTGR lattices containing ^{233}U . (16,23)

A calculation of k_{∞} with the end caps included in the cell is described in Appendix A. It is shown that the end caps have little effect on the above result.

FIGURE 5. Comparison of Experimental and Theoretical k_{∞}

VII. CONCLUSIONS

This report describes the results of perturbation experiments designed to measure reactivity effects important in the design of a MSBR. The attempt has been made to provide herein all data necessary for an independent analysis of these effects.

Derived from the experimental measurements is a value of k_{∞} that may be compared with calculated results. Using cross sections and methods current at BNW, the experimental change in k_{∞} with temperature was found to be significantly less than that calculated. This result is in agreement with results from two other HTLTR experiments utilizing ^{233}U .

ACKNOWLEDGEMENTS

The design of the MSBR experiment originated in discussions between Battelle-Northwest and Oak Ridge National Laboratory. The perturbation cells and material worth samples were conceived by G. L. Ragan of ORNL and much of the final design was due to E. C. Davis of BNW. The strong support of the HTLTR operations staff enabled the experiment to be carried out with the desired accuracy within time limits. Discussions with other members of the HTLTR staff also contributed to the success of the experiment.

APPENDIX A

Evaluation of k_{∞} with End Caps Included

One of the largest uncertainties in the method of evaluating the experimental k_{∞} is due to the necessity of accounting for the end cap effect. As described in Section V, the end cap graphite worth is evaluated in the void and subtracted from the central cell worth. The value of k_{∞} evaluated using the net cell worth is then compared to the value calculated for a cell without any end caps.

A second method of evaluating k_{∞} is to leave the end caps in the central cell. Parameters for the cell including the end caps must then be calculated. The simplest technique is to smear the end caps into the cell moderator and re-do the EGGNIT and GRANIT calculations. The moderator density was kept the same and the cell was enlarged to include the extra graphite. The Dancoff correction in EGGNIT was left unchanged. The parameters and k_{∞} calculated by this method are presented in Table XIV.

Another method of including the end caps was also tried. In this method, the two group homogenized cross sections for the cell without end caps were used in DTF to calculate the end cap effect in slab geometry. Using the fluxes from this calculation, suitable averages over the cell result in the parameters given in Table XV. Calculations were only carried out at 20° and 1000°C, but a comparison with Table XIV indicates that results obtained from the two methods are in good agreement.

Using the parameters from Table XIV, k_{∞} for the cell with end caps may be evaluated. This evaluation is summarized in Table XVI, which is similar to Table XI for the case with end caps subtracted.

A comparison of the results with the end caps included with those for the end caps subtracted indicates qualitatively little difference. The k_{∞} with end caps is in slightly better agreement with the calculation but the temperature coefficient is in slightly worse agreement. The calculated change in k_{∞} at room temperature due to the end caps is 0.0034 compared to the measured 0.0055. Some of this difference may be due to the necessity for measuring the end cap worth in the void. However, it is seen that the end cap effect can not account for the discrepancy in temperature coefficient.

TABLE XIV
PARAMETERS WITH END CAPS SMEARED

		20°	300°	627°	1000°
Σ_1^a	cm ⁻¹	1.08310 x 10 ⁻³	1.16254 x 10 ⁻³	1.22719 x 10 ⁻³	1.28474 x 10 ⁻³
Σ_{12}	cm ⁻¹	2.72189 x 10 ⁻³	2.69237 x 10 ⁻³	2.66449 x 10 ⁻³	2.63633 x 10 ⁻³
τ	cm ²	318.72	314.76	311.94	309.75
$\eta_1 f_1$		0.73814	0.68326	0.64298	0.61306
p		0.71535	0.69843	0.68466	0.67235
Σ_2^a	cm ⁻¹	5.03983 x 10 ⁻³	4.28520 x 10 ⁻³	3.71583 x 10 ⁻³	3.28939 x 10 ⁻³
L^2	cm ²	192.07	225.32	258.16	291.30
$\eta_2 f_2$		1.17858	1.18358	1.19337	1.20550
$\eta_2 f_2 p$		0.84310	0.82665	0.81705	0.81052
$\eta_1 f_1 (1-p)$		0.21011	0.20605	0.20276	0.20087
B^2	cm ⁻²	1.131 x 10 ⁻⁴	0.662 x 10 ⁻⁴	0.383 x 10 ⁻⁴	0.210 x 10 ⁻⁴
L_B^2		0.02173	0.01492	0.00988	0.00611
k_∞		1.0513	1.0311	1.0185	1.0106

TABLE XV
PARAMETERS WITH END CAPS IN DTF

		<u>20°</u>	<u>1000°</u>
Σ_1^a	cm^{-1}	1.07979×10^{-3}	1.28155×10^{-3}
Σ_{12}	cm^{-1}	2.69735×10^{-3}	2.61320×10^{-3}
τ	cm^2	321.19	311.94
$\eta_1 f_1$		0.73632	0.61119
p		0.71412	0.67095
Σ_2^a	cm^{-1}	4.97916×10^{-3}	3.26701×10^{-3}
L^2	cm^2	194.31	293.24
$\eta_2 f_2$		1.17863	1.20551
$\eta_2 f_2 p$		0.84168	0.80884
$\eta_1 f_1 (1-p)$		0.21050	0.20111
B^2	cm^{-2}	1.099×10^{-4}	0.182×10^{-4}
$L^2 B^2$		0.02136	0.00534
k_∞		1.0503	1.0092

TABLE XVI				
EVALUATION OF k_{∞} WITH END CAPS				
	20°	300°	627°	1000°
$\Delta\rho^{\text{cell}}$ ϕ	3.28	1.91	1.39	1.24
$(\Delta\rho^{\text{Cu}}/M^{\text{Cu}})$ ϕ/gm	0.0173	0.0174	0.0170	0.0169
$1 + \alpha$	1.117	1.119	1.121	1.124
$(\Sigma\phi V)^{\text{cell}}/(\Sigma\phi V)^{\text{Cu}}_{\text{gm}}$	4844	4897	4950	5008
$\Delta\phi/\phi$	-0.004	-0.005	+0.001	+0.002
$\Delta\phi^+/\phi^+$	-0.015	-0.020	-0.024	-0.025
A	0.0439	0.0252	0.0185	0.0164
b_1	0.7757	0.7716	0.7631	0.7546
b_2	0.30	0.25	0.20	0.16
k_{∞}	1.0346	1.0196	1.0142	1.0124

APPENDIX B

Material Descriptions and Analyses

TABLE XVII
 $\text{ThO}_2\text{-}^{233}\text{UO}_2$ PARTICLE DESCRIPTION AND ANALYSIS

Uranium Isotopic Analysis (a)

<u>Isotope</u>	<u>Concentration (at.%)</u>
^{232}U	6×10^{-4} (nominal)
^{233}U	97.45
^{234}U	1.047
^{235}U	0.092
^{236}U	0.006
^{238}U	1.41

<u>Composition</u>	<u>Batch 20 (b)</u>	<u>Batch 22^(b)</u>
Kernel Diameter (μm)	279 ± 26	319 ± 21
Coating Thickness	88 ± 12	107 ± 12
Assumed Kernel Density (g/cm^3)	10.00	10.00
Coating Density (g/cm^3)	1.87	1.87
U (wt.%)	14.32	13.72
Th (wt.%)	40.05	38.35

(a) Data supplied by ORNL.

(b) Fuel blend was composed of 43.73% by weight of Batch 20 particles and 56.27% of Batch 22 particles.

TABLE XVIII
²³⁵UC₂ PARTICLE DESCRIPTION AND ANALYSIS

Uranium Isotopic Analysis (a)

<u>Isotope</u>	<u>Concentration (wt.%)</u>
²³⁴ U	0.567 ± 0.005
²³⁵ U	92.93 ± 0.09
²³⁶ U	0.300 ± 0.003
²³⁸ U	6.20 ± 0.09

Kernel Size Distribution (b,c)

<u>Kernel Diameter (μm)</u>	<u>Weight Percent</u>
250-280	19
280-305	26
305-330	20
330-355	17
355-380	10
>380	8

Composition of Coated Particles (d)

U (wt.%)	67.94
Coating Thickness (μm)	65 average
Coating Density (g/cm ³)	2.01
Kernel Density (est.) (g/cm ³)	10.5
Impurities	
F + Cl	20 ppm
N ₂	135 ppm
Equivalent Boron	<4 ppm

- (a) Measured by BNW; uncertainties at the 95% confidence level.
(b) Measured by BNW using x-radiography.
(c) Particles screened before coating to 250-420 μm. Some particles larger than 420 μm observed.
(d) Data supplied by Gulf General Atomic Corporation.

TABLE-XIX
ZrO₂-²³⁹PuO₂ PARTICLE DESCRIPTION AND ANALYSIS^(a)

Pu Isotopic Analysis

<u>Isotope</u>	<u>Concentration (wt.%)</u>
²³⁸ Pu	0.01
²³⁹ Pu	97.12
²⁴⁰ Pu	2.65
²⁴¹ Pu	0.21
²⁴² Pu	0.011
²⁴⁴ Pu	<0.002

Particle Composition

<u>Material</u>	<u>(wt.%)</u>
Pu	3.34
PuO ₂	3.79
ZrO ₂	50.08
C	46.13 (by subtraction)
Nominal Kernel diameter (μm)	150 ^(b) (b,c)
Nominal Coating Thickness (μm)	100

- (a) Data supplied by ORNL.
 (b) No measurements available.
 (c) 25 μm inner low density layer and 75 μm outer high density layer.

TABLE XX

ANALYSIS OF HASTELLOY N USED IN MSBR LATTICE EXPERIMENTS IN HTLTR (a)

Element	Weight Percent	
	1/4 in. Plates	Foil (0.001 in.)
Cr	6.7	8.3
Fe	3.7	4.3
Mo	17.2	17.7
Ni	71.6	69.0
Mn	0.69	0.66
Co	0.10	0.07

(a) Data supplied by ORNL.

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