ORGANIC-COOLED, HEAVY WATER-MODERATED, U-233 FUELED LATTICE EXPERIMENTS

CFSTI PRICES

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Introduction

Measurements of material buckling and thermal neutron flux distributions were made in exponential lattices containing the "kilo-rod" fuel pins. The purpose of these measurements was to provide a few definitive data points which can be used to verify design calculations for large power reactors utilizing uranium-233 and thorium fuel with organic coolant and heavy water moderator. Consequently, a few lattices were chosen which were consistent with the conceptual design of such a reactor, after consultation with representatives of the Babcock & Wilcox Co.

The "kilo-rod" fuel pins are not particularly well suited for these experiments because of their high U-233 content and short active fuel length. Consequently, stainless steel canisters were incorporated in the design to reduce the material buckling and to allow full utilization of the 800 "kilo-rod" fuel pins which were available. In addition, it was decided to make the measurements in a bare assembly, i.e. unreflected assembly, in order to minimize the effects of neutron spectral transients

which may be generated at the core-reflector interface.

Comparisons are made between the experimental data and calculations using the Methuselah reactor code. No attempt has been made to compare this reactor code with others, since it was chosen as the only appropriate code which was immediately available at BNL. Moreover, it proved to be convenient in planning the experimental program and interpreting the data as it was generated.

Description of Lattices and Facility

The exponential assemblies were erected on the top thermal column of Neutron Source Reactor I, as shown in figure (1). A boral shutter between reactor and exponential assembly was used to separate spurious neutron source effects, which have their origin in gamma radiation from the reactor and U-232 in the fuel elements, and also from α -n reactions in the fuel.

The fuel pins were fabricated at the Kilorod Facility of Oak Ridge National Laboratory. They consist of a U-233 O_2 - ThO_2 vibratory-compacted core in a zircaloy tube. Detailed specifications are given in Table I.

Cluster-type fuel elements were composed of 31 fuel pins in a stainless steel canister, with Dowtherm A coolant. The fuel pins were located on a triangular grid with a 0.6767 in. pitch, omitting the six corner positions of the outermost hexagon.

Specifications for the stainless steel canisters are given in Table II. Dowtherm A specifications are included in Table III and heavy water specifications are in Table IV. One lattice was composed of fuel elements containing only 24 fuel pins, the central 7 pins having been removed and replaced by a solid aluminum plug 1.755 in. in diameter (Table V).

The lattice tank was square, 42.5" I.D., constructed of 1/2" aluminum and was enclosed on the sides by 1/4" boral plate. In addition, a 6" thick paraffin shield, encased in 1/2" plywood surrounded all lattices except No. 1.

U-232 Gamma Radiation

The presence of U-232 in the fuel elements is the cause of an anomalous radiation problem which can be attributed to the unique decay scheme of U-232 and its daughter products. Measurements of the alpha spectrum from a sample of fuel material indicate that there are about 23 ppm U-232 in the uranium. ⁽¹⁾ Just prior to the fabrication of the fuel pins most of the daughter products of U-232 were chemically removed. However, it is not possible to chemically separate U-232 and U-233. Consequently the intensity of gamma radiation, due largely to Pb-212, Bi-212 and Tl-208, increases with time as the daughter products build up according to the decay scheme shown in Figure 2. Figure (3) compares the calculated and observed gamma activity one meter from a fuel pin since fabrication

in 1963. The three test pins contain no fission products since they have never been exposed to neutrons. The irregular shape of the data points near the origin indicate incomplete separation of the U-232 daughter products. The calculated curve, which includes self absorption effects, underestimates the observed radiation by about 27 per cent. This difference may be due to a low value for the U-232 concentration, incomplete separation of daughter products, or an over estimation of the gamma self-absorption effects.

As the fuel pins are exposed to neutrons in the exponential assembly the fission product inventory should increase with time. However, it was found that the long lived-fission product gamma activity (i.e. > 2 weeks) was negligible compared to the U-232 decay chain activity.

Dowtherm A Diffusion Constant

Dowtherm A is a mixture of diphenyl and diphenyl oxide in the proportion approximately 26.5 wt. % and 73.5 Wt. % respectively. However, since it is a commercial grade material and not necessarily stoichiometric it was felt prudent to measure the neutron diffusion parameters on the same material which was used for the exponential experiments. ⁽²⁾ Table VI gives the results of quantitative analyses on the two-55 gallon drums of Dowtherm A.

The diffusion length, L , was measured by axial and radial flux

traverses in a tank of Dowtherm A, 24" diameter and 25" high. The diffusion parameters, λ and $v\bar{D}$ were determined by observing the decay rate of thermal neutrons in Dowtherm A. Table VII gives the results of both exponential and pulsed measurements at 16°C. The range of geometric buckling for the pulsed measurements was not sufficiently large to warrant inferring a value for the diffusion cooling constant. The best values for the diffusion parameters appear to be those values derived from the combined exponential and pulsed data.

Material Buckling Measurements

Material bucklings were measured by means of indium foil traverses in exponential assemblies at 21°C. Vertical, or axial, traverses were accomplished with bare indium foils (.005" and 0.10" x .387"), mounted on zircaloy-2 tubes, in the heavy water. Foils were spaced at 2" intervals between 8 and 42 inches along the vertical axis. Because of boundary effects, only those foils between 14 and 36 inches were usually used in determining the relaxation length, L . The probable error in L was derived from a statistical analysis of 8 separate measurements.

Radial flux traverses were made with both bare and cadmium covered indium foils mounted at the mid-plane of the lattice, in heavy water. The cadmium ratios deviated noticeably from the norm at distances greater than 15" from the center. Therefore, only those foils at distances less than 15" from the center were

used to determine the radial buckling.

The extrapolated widths were calculated separately for foils at correlated positions in both x and y traverses, and for bare and cadmium covered foils. The average extrapolated width, $\bar{x}$, as listed in Table VIII is the average of all traverses in both the x and y directions, since there appeared to be no discrimination with direction. Probable errors for $\bar{x}$ and L were calculated from the statistical deviation of several independent runs.

The experimental material bucklings were corrected to a uniform D₂O purity (99.8%) through the use of Methuselah Calculations as shown in Fig. (4). D₂O purity is quoted in molar per cent, $\frac{D_2O}{D_2O+H_2O}$. The slopes of the calculated curves were used to make the correction for D₂O purity. Also, since lattice No. 4 was not calculated as a function of D₂O purity, the curve for lattice No. 3 was used in making that correction.

In lattice No. 4 the presence of large air channels in the fuel elements may distort the interpretation of the buckling measurements because of source neutrons streaming up the channels, or because of anisotropy in the neutron migration area. Measurements of the neutron relaxation lengths in the central fuel pin and in the center of the D₂O region (41.77 ± 0.25 cm. and 41.40 ± 0.25 cm. respectively) indicated that streaming effects are negligible. An estimate of the neutron migration area anisotropy

gives a ratio of 1.02 for the ratio of migration areas in the axial and radial directions. If this anisotropy were applied to the experimental data it would reduce the material buckling from 8.57 m^{-2} to 8.45 m^{-2} . In view of the uncertainty in the correction, and the small effect on the inferred material buckling, the anisotropy effect was considered to be negligible.

Thermal Neutron Activation

The relative activation rates as a function of position in the lattice were measured for dysprosium and lutetium in lattices 2, 3, 4 and 5. Foils were simultaneously placed in the fuel pins, in the coolant and in the moderator. After exposure, the resultant β activity gave the relative activation rate for the various foil positions.

The foils were exposed in the lattice in the form of sector foils 0.004" thick Dy-Al (5 Wt. % Dy), and 0.010" thick Lu-Al (10 Wt. % Lu). The foil arrangement within the canister, Fig. (5), was the same for lattices 2, 3 and 4. The arrangement in lattice 5, with the aluminum plug replacing the seven central fuel pins, is shown in Fig. (6). The foil positioning in the D_2O moderator is shown for the two different lattice pitches in Fig. (7).

The foils located inside the fuel pins and in the D_2O moderator had the same diameter (0.425") as the fuel. The sector foil located in the coolant was equivalent in size to the smallest unit

cell in the cluster minus 0.001" clearance for the fuel rods and 0.020" clearance for the inside wall of the canister. The foils in the moderator were fastened to mylar tape that was strung on a wire basket, fastened to the outside of the canister, Fig. (8). The sector foil in the coolant was held in vertical position by small teflon rings.

The fuel rods in the center section Fig. (8) were made up of removable pellets .425" dia. x .35" long. These pellets had a density of 9.17 g/cc compared to 8.96 g/cc for the vibratory compacted fuel rods, but with the smaller diameter result in the same linear fuel density.

The use of lutetium as a detector material required a cadmium covered activation. Subtracting the cadmium covered activity from the bare activity gives the thermal activation of Lu^{176} (6.8 day half life Lu^{177}). The details for the cadmium covers used inside the canister are shown in Fig. (9). Standard cadmium pill boxes were used in the D_2O moderator and a uniform thickness of 0.028" was used throughout.

After exposure, the foils were β counted in four 2" end window gas flow proportional counters. The sector foil located in the moderator was cut into ten pieces, Fig. (5), with a specially designed shear to facilitate counting and to give fine structure in the coolant. The lutetium foils were counted a

minimum of three days after exposure to allow for the decay of 3.7 hours half life Lu^{176} . All foils were calibrated by placing them on a spinning wheel, exposing them to the thermal column of NSR II and counting the resulting β activity.

The results of the measurement are given in tabular form, Table IX, and graphic form, Figs. (10-13). The results were normalized to the foil in the central fuel pin except in lattice 5 where the foil in pin 3 was used for normalizing. The ratio of the average Dy and Lu activation rates in the coolant to the fuel as well as the ratio in the moderator to the fuel have been computed and are shown in Table X. A comparison is made to calculations using the Methuselah code. The results of the Methuselah calculations are also shown in Figs. (10-13). In one measurement, a dysprosium foil was taped on the outside of the canister to determine if the flux dipped appreciably at the stainless steel canister. There appeared to be no flux dipping at the canister as can be seen in Fig. (11).

The cadmium covered lutetium activity had to be corrected for thermal leakage along the outer edge, and in lattice 5 along the outer and inner edge. This was caused by not having space to include cadmium along these edges. The data was also corrected for the fact that the sector foil in the coolant was under size on the outer edge by 0.020" to allow for assembling the cluster.

No corrections were made for foil perturbations or for perturbations caused by the use of cadmium.

Methuselah Calculations

Before the Methuselah program ^(3,4) was applied to the actual cluster lattices, some preliminary runs were made on uniform lattices to test the program against Hammer ⁽⁵⁾ as well as against experimental data. The Methuselah results turned out to be considerable in error, due primarily to incorrect input data for the epithermal absorption and fission in U-233. New group cross-sections for the three fast groups were prepared, based on Feiner and Esch's ⁽⁶⁾ recommended data for the fission integral and the epithermal α . The values used, and the group cross-sections derived are given in Table XI.

The group cross-sections given are those corresponding to an infinitely dilute absorber. In the Methuselah program self-shielding can be taken into account for group three by substituting the dilute value by the expression

$$\sigma_3 = A + C \sqrt{\frac{\Sigma_p^1}{\Sigma_p^1 + DN}} \quad (1)$$

where A, C and D are constants specific for the resonance absorber and Σ_p^1 is the effective macroscopic potential scattering cross-section $\Sigma_p^1 = \Sigma N_i \sigma_p^i + \frac{S}{4V}$.

A + C must obviously be equal to the dilute value of σ_3 . The relation between A and C was furthermore chosen the same as that

originally given in the Methuselah library (2A₂C). D, finally, was determined by requiring that the self-shielding as obtained from Eq. 1 should be the same as that calculated in Hammer for the 3% enriched U-233 fuel rods. The values of the constants for absorption then became

$$A = 30.8$$

$$C = 61.6$$

$$D = 785$$

and for $\bar{\nu}$ x fission

$$A = 65.1$$

$$C = 130.2$$

$$D = 785$$

A new test calculation was made on a 3:1 moderator to fuel, uniform lattice. Using the measured buckling as input, Methuselah gave a k_{eff} of 1.020 with the new U-233 cross-sections. Hammer came out slightly higher, or $k_{\text{eff}} = 1.030$. No detailed investigation was made to find the reason for the difference between Methuselah and Hammer. The 2200 m/s cross-sections for absorption in thorium and fission in U-233 differ somewhat but in the wrong direction. The ratio of the U-233 fission cross-section to that for absorption in Th is about 3% larger in the Methuselah library than in the Thermos library.

No simple and justifiable change could be made in the Methuselah library to obtain a k_{eff} closer to unity for the test run. As it is not likely that the agreement should improve for cluster lattices, discrepancies between calculations and experiments of the order of several percents in k_{eff} can be expected for such systems.

Material buckling, B_m^2 , and infinite multiplication factor, k^∞ , were calculated as a function of lattice pitch (square array) and are indicated by the smooth curves in Figures (14) and (15). Since the results of lattice No. 4 with air coolant are somewhat anomalous, Figures (16) and (17) show the corresponding calculations as the coolant density, both D_2O and Dowtherm A, is reduced from normal density to zero. The experimentally determined bucklings are shown by cross marks in Figure (14). The points in Figures (15-17) indicate the results of Methuselah calculations.

Activation rates for manganese and lutetium were calculated by adding 0.00001 per cent of these elements to all regions and then comparing the results of the absorption edit. Manganese activation distribution was used in place of dysprosium because they are both essentially $1/v$ in the thermal energy region, and because dysprosium was not included in the Methuselah Library.

Summary

Material bucklings and thermal flux activation rates have been measured for four lattices containing U-233 and thorium oxide with D_2O moderation. Accuracy of the buckling measurements is essentially limited by the short fuel length and the small number of clustered fuel elements. If one assumes a migration area of 200 cm^2 , an uncertainty of $\pm 0.22 \text{ m}^{-2}$ in the buckling corresponds to about ± 0.004 in k_{eff} . Although one would hope for a smaller uncertainty in a normal uniform-lattice experiment, there are no obvious ways in which the uncertainty can be reduced in these experiments.

The Methuselah calculations underestimate the flux depression in the clustered elements by quite a large factor. However, the effect on reactivity is relatively small because of compensating absorption in the stainless steel canister.

Methuselah overestimates the buckling by about 3 m^{-2} in most cases, with a corresponding overestimate in k_{eff} of about 0.055. These differences are somewhat greater than the British experience with the Methuselah program, although Campbell ⁽⁷⁾ reports differences as large as 0.035, usually in the same direction as those observed here. In conclusion, there is a need for improvement in the reactor calculations, although the source of error is not obvious.

REFERENCES

- (1) W. Tunney, " U^{232} Content in $U^{233}O_2-ThO_2$ ", BNL internal memorandum, RP-311, May 13, 1965.
- (2) G. A. Price & H. H. Windsor, "Diffusion Parameters of Dowtherm A", BNL internal memorandum, RP-366, March 28, 1966.
- (3) D. Hicks, "Few-Group Nuclear Design Methods for Heavy Water Reactor," Proc. Heavy Water Lattices" Second Panel Report, IAEA, 1963.
- (4) R. Alpair, "METHUSELAH I, A Universal Assessment Programme for Liquid Moderated Reactor Cells, Using IBM 7090 or Stretch Computers", AEEW-R 135 (1964).
- (5) John E. Suich & Henry C. Honeck, "Heterogeneous Analysis by Multigroup Methods of Epithermal Reaction," Transactions of the A.N.S. Vol. 8, No. 2, p. 511 (1965).
- (6) F. Feiner and L. J. Esch, "Survey of Capture and Fission Integrals of Fissile Materials, "ANS Topical Meeting, San Diego, 1966.
- (7) C. G. Campbell et al. "Reactor Physics Studies for Steam Generating Heavy Water Reactors", Third Geneva Conf. 3, 117 (1965).

TABLE I

 $U^{233}O_2$ - ThO_2 Fuel Pin Composition

Av. Density = 8.9618 gm/cm³; diameter = 0.430 in. = 1.09220 cm.

Active length = 42.5 in. = 107.98 cm.

$U^{233}/(U^{233} + Th)$ wt. ratio = 0.03000

<u>Isotope</u>	<u>Fractional Wt.</u>	<u>Atoms/cm³</u>
O^{16}	0.121197	0.408832×10^{23}
Th^{232}	0.851764	0.198155
U^{233}	0.026343	0.0061021
U^{234}	0.000394	0.0000909
U^{235}	0.000012	0.0000027
U^{238}	0.000289	0.0000655
B	0.0000044	0.0000220

Clad Composition: Zircaloy-2; density = 6.8365 gm/cm³; O.D.
= 0.499 in. = 1.26746 cm; I.D. = 0.430 in.
= 1.09220 cm

<u>Isotope</u>	<u>Fractional Wt.</u>	<u>Atoms/cm³</u>
Zr	0.9827	0.443550×10^{23}
Sn	0.0145	0.005030
Cr	0.0010	0.000792
Fe	0.0013	0.000958
Ni	0.0005	0.000351
Co	5×10^{-6}	0.0000035
B	1.4×10^{-6}	0.0000053
Cd	0.5×10^{-6}	0.0000002
Hf	3×10^{-6}	0.0000007

TABLE II

Stainless Steel Canister Specifications

Type: SMLS Croloy 304 EF, CD, AW (HT. 29076)
O.D.: 4.505 in. → 4.520 in.; av. = 4.509 in. = 11.453 cm.
Wall Thickness: .114 in. → .130 in.; av. = 0.122 in. = 0.310 cm.
Wt./Unit Length: 85.04 ± 0.20 gm/cm.
Density: 7.836 gm/cm³
Chemical Analysis:

	<u>Fractional Wt.</u>	<u>Atoms/cm³</u>
C	.00061	0.0002x10 ²³
Mn	.0164	0.1409
P	.00018	0.0027
S	.00013	0.0019
Si	.0052	0.0875
Ni	.1028	0.8266
Cr	.1865	1.6922
Fe	.68818 (remainder)	5.8150

Note:

Density and atom densities conform to the average OD, average wall thickness, and weight per unit length. Variations in OD and wall thickness depend upon the azimuthal angle, although the tubes are quite uniform along their length.

TABLE III

Dowtherm A Specifications

Supplier: Dow Chemical Co.
Lot No: 10215
Density: 1.0661-.000837 (T-16) $\pm$.0010

Chemical Analysis:

	<u>Wt. %</u>	<u>Atoms/cm³ (16°C)</u>
H	6.05 $\pm$.05	0.3850x10 ²³
C	86.93	0.4647
O	7.02	0.0282

TABLE IV

Moderator Specifications

Material: Heavy water (99.8 molar percent D₂O)

$$\rho = 1.105$$

$$T = 21^{\circ}\text{C}$$

<u>Isotope</u>	<u>Fractional Weight</u>	<u>Atoms/cm³</u>
H	0.0002	0.0013 x 10 ²³
D	0.1996	0.6642 x 10 ²³
O	0.8002	0.3328 x 10 ²³

TABLE V

Aluminum Plug Specifications

Type: 6061 aluminum
Diameter: 1.755 in. = 4.458 cm.
Density: 2.644

<u>Element</u>	<u>Fractional Wt.</u>	<u>Atoms/cm³</u>
Si	.006	.003465
Fe	.007	.002033
Cu	.003	.000766
Mn	.0015	.000442
Mg	.0010	.000667
Cr	.0025	.000780
Zn	.0025	.000620
Ti	.0015	.000508
Al	.975	.586224

TABLE VI

Dowtherm A Composition (Wt. %)

	<u>Drum No. 1</u>	<u>Drum No. 2</u>	<u>Average</u>
Density @27°C	1.0579	1.0559	1.0569 $\pm$.0005
H Concentration	6.03%	6.07%	6.05% $\pm$.05%
C "	86.80%	87.07%	86.93%
O "	7.17%	6.86%	7.02%

TABLE VII

Dowtherm A

16°

$\rho = 1.0661 \pm .0010$

	Exponential	Pulsed	Exp. & Pulsed
L (cm.)	4.240 $\pm$.024		
1/L ⁻² (cm ⁻²)	.05562 $\pm$.00061		
λ_o (sec ⁻¹)		2914 $\pm$ 64	2831 $\pm$ 22
v $\bar{D}$ (cm ² sec ⁻¹)		46648 $\pm$ 3747	50379 $\pm$ 927
σ_a (per H Atom) at 2200 m/s, barns)			0.333 $\pm$.003

TABLE VIII

Material Buckling

Lattice No.	Array	Fuel El.	Pitch (in.)	Reflector	Coolant	D ₂ O Purity
1	4x4	31 pins	10.65"	boral	DowthermA	99.76%
2	4x4	"	"	boral + paraffin	"	99.75%
3	5x5	"	8.50"	"	"	99.72%
4	5x5	"	"	"	air	99.69%
5	5x5	24 pins + Al plug	"	"	DowthermA	99.61%

Lattice No.	$\bar{x}$ (cm.)	L (cm.)	$B_x^2 + B_y^2$ (m ⁻²)	$1/L^2$ (m ⁻²)	B_m^2 (exp.)	B_m^2 (99.8%D ₂ O)	B_m^2 (METH)
1	115.98 ± 1.61	27.15 ±0.16	14.58 ±0.15	13.56 ±0.16	1.02 ±0.22	1.07 ±0.22	4.1
2	115.47 ± 0.71	26.58 ±0.12	14.80 ±0.18	14.15 ±0.13	0.65 ±0.22	0.71 ±0.22	4.1
3	115.90 ± 0.74	31.67 ±0.17	14.69 ±0.19	9.97 ±0.11	4.72 ±0.22	4.78 ±0.22	7.7
4	117.07 ± 0.53	41.40 ±0.25	14.40 ±0.13	5.83 ±0.07	8.57 ±0.15	8.66 ±0.15	9.2
5	115.42 ± 0.61	27.37 ±0.08	14.82 ±0.16	13.35 ±0.08	1.47 ±0.18	1.62 ±0.18	3.7

TABLE IXThermal Neutron Activations

<u>Foil No.</u>	<u>Lattice No.2</u>		<u>Lattice No.3</u>		<u>Lattice No. 4</u>		<u>Lattice No. 5</u>	
	<u>Dy</u>	<u>Lu</u>	<u>Dy</u>	<u>Lu</u>	<u>Dy</u>	<u>Lu</u>	<u>Dy</u>	<u>Lu</u>
1	1.272	1.258	1.217	1.156	1.156	1.046	-	-
2	1.506	1.401	1.339	1.220	1.247	1.142	-	-
3	1.701	1.571	1.507	1.374	1.322	1.209	1.184	1.073
4	2.276	1.973	1.861	1.620	1.548	1.359	1.281	1.167
5	2.569	2.174	2.099	1.795	1.595	1.399	1.375	1.219
6	3.873	3.002	3.000	2.253	1.916	1.605	1.871	1.572
7	4.187	3.368	3.065	2.457	1.995	1.708	2.029	1.641
8	4.251	3.328	3.100	2.470	1.981	1.683	2.088	1.687
9	4.468	3.354	3.341	2.559	1.958	1.612	2.232	1.745
10	3.084	2.540	2.445	2.001	1.796	1.506	1.634	1.395
11	1.000	1.000	1.000	1.000	1.000	1.000	-	-
12	1.198	1.147	1.120	1.073	1.086	1.023	-	-
13	1.593	1.572	1.356	1.359	1.264	1.136	1.000	1.000
14	1.859	1.696	1.581	1.425	1.356	1.252	1.124	1.016
15	2.790	2.368	2.141	1.788	1.571	1.360	1.430	1.279
16	7.178	5.086	4.902	3.421	3.461	2.	3.218	2.336
17	9.410	6.469	6.099	4.084	4.799	3.336	4.014	3.815
18	10.436	6.988	6.729	4.496	5.467	3.752	4.389	3.098
19	10.608	7.288	6.934	4.623	5.685	3.866	4.514	3.153
20	6.967	4.993	4.797	3.326	3.368	2.476	3.138	2.301
21	8.705	6.030	5.696	3.850	4.288	3.012	3.722	2.646
22	9.226	6.384	5.997	4.020	4.578	3.199	3.886	2.793

TABLE X

Average Activation Ratios

Lattice No.	<u>Activation Rate in Coolant</u>				<u>Activation Rate in Moderator</u>			
	<u>Activation Rate in Fuel</u>				<u>Activation Rate in Fuel</u>			
	Dysprosium		Lutetium		Dysprosium		Lutetium	
	Exp.	Meth.	Exp.	Meth.	Exp.	Meth.	Exp.	Meth.
2	1.451	1.456	1.334	1.441	4.433	3.858	3.412	3.389
3	1.408	1.419	1.315	1.405	3.557	3.062	2.688	2.708
4	1.238	-	1.198	-	3.320	3.094	2.590	2.657
5	1.356	1.380	1.224	1.369	3.080	2.657	2.186	2.373

TABLE XI

 U^{233} Group Constants

Fission integral, $0.5 < E < 10^7$ ev: $780 \pm 40b$

Epithermal α : $.175 \pm .008$

Group	Energy Interval	<u>Resonance Integral</u>		<u>Group Cross Section</u>		$\bar{\nu}$
		Fission	Capture	Absorption	Fission	
1	10 Mev-821kev	5	1	2.4	2.0	2.80
2	821 kev-5.5kev	21	4	5.0	4.2	2.53
3	5.5 kev-.625ev	709	130	92.4	78.1	2.50

Figure 1.

Nuclide	Gamma Energy	Yield
Pb ²¹²	0.250	0.40
	0.720	0.19
	0.830	0.19
	1.03	0.06
Bi ²¹²	1.34	0.05
	1.61	0.07
	1.81	0.07
	2.2	0.035
Tl ²⁰⁸	0.510	0.25
	0.582	0.80
	0.859	0.15
	2.62	1.00

Figure 2.

Figure 3. Gamma Radiation Build-Up in $U^{233}O_2-ThO_2$ Fuel Rods

Figure 4. Variation of Material Buckling With D_2O Purity

Figure 5. Sector Foil Positions in Canister

Figure 6. Sector Foil Positions in Canister With Aluminum Plug

FOIL NO.	DIMENSION FROM C CANISTER	
	10.65 RATIO	8.50 RATIO
16	2.73	2.50
17	4.29	3.67
18	5.94	4.87
19	7.50	5.99
20	2.73	2.50
21	4.02	3.42
22	5.31	4.25

Figure 7. Foil Positions in D_2O Moderator

Figure 8. Organic Cooled Cluster Lattice

Figure 9. Cadmium Arrangement

Figure 10.

Figure 11.

Figure 12.

Figure 13.

Figure 14. Material Buckling vs Lattice Pitch

Figure 15. Infinite Multiplication Factor vs Lattice Pitch

Figure 16. Material Buckling vs Coolant Density

Figure 17. Multiplication Factor vs Coolant Density