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An Experimental Parametric Study of the Effects
of Control Rods on the Prompt Neutron Decay
Constant in Multiplying Media

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April 1962

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AN EXPERIMENTAL PARAMETRIC STUDY OF THE EFFECTS
OF CONTROL RODS ON THE PROMPT NEUTRON DECAY CONSTANT
IN MULTIPLYING MEDIA

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ABSTRACT

The effect of control rods of various geometries and absorber materials on the prompt neutron decay constant is measured. Experiments were performed in the Critical Experiment Facility at Vallecitos Atomic Laboratory on a diversity of core lattices and moderators, namely, 1.3, 3.00, and 93.2 per cent enriched U-235 fuels with light and heavy water, organic, and graphite.

INTRODUCTION

This document is the final report of the results of measurements of the effect of control elements on a broad range of thermal reactor types. The purpose of the program is to provide bench marks of known control element worth which may be used for establishing the reliability of theories of reactor control. The method used was to measure the worth by pulsed neutrons source technique of arrays of control elements in eleven different reactors. A parallel theoretical study was carried out to relate the experimental results to existing theory and to extend theory where possible.

The types of thermal reactors investigated included those combinations of fuel and moderator which are typical of the reactors being designed and built by the atomic energy industry. The control elements investigated are slabs, cylinders, and flux traps.

The pulsed neutron technique used here has been described by Simmons and others⁽²⁾. Briefly, the method consists of the injection of a burst of neutrons into a subcritical multiplying system and observing the fundamental decay of the neutron population. After a time required for source neutron thermalization and higher mode decay, the thermal neutron density as a function of time is

$$n(t) = n_0 e^{-\alpha t} + n_d$$

Here t is the time after the initial source pulse at $t = 0$, and α is the prompt neutron decay constant. It is this quantity that we measure. No practical difficulty is caused by the slowly decaying delayed tail, n_d , in flux time dependence. Characteristic lifetimes of the prompt neutrons in thermal lattices are of the order of a few milliseconds. The mean lifetime of the delayed portion is about 10 seconds. The tail is thus virtually a steady-state background.

The conventional description of far subcritical systems in terms of reactivity is difficult, because of the lack of well defined experiments for its measurement. It appears more useful to characterize such systems by their decay constants, which are directly observable.

The first part of this report is a description of systems and techniques.
The second part contains results of the measurements.

PART I: DESCRIPTION OF SYSTEMS AND TECHNIQUES

A. CORE SYSTEMS

The measurements were performed on eleven basic core configurations in the Critical Experiment Facility⁽³⁾, using variable moderator height for reactivity control. The fuel elements, cylindrical rods of approximately 0.5 inch O.D., are contained in an open cylindrical tank of 6 feet diameter and height. A bottom grid sheet, carefully aligned with an upper one, provides for uniform and rigid lattices. A typical lattice is shown in Figure 1.

The 1.3 per cent and 3.0 per cent enriched fuel is uranium dioxide (UO_2) in pellets clad in aluminum and stainless steel, respectively. The 93.2 per cent enriched fuel is an uranium-aluminum alloy clad with aluminum. For the 1.3 and 93.2 per cent fuel the active region is 48 inches long, and 72.75 inches long for the 3 per cent fuel. Complete fuel design details are given in Table I.

Four different types of moderator are used; namely, demineralized light water, heavy water, AGOT graphite (all at 20°C), and an organic mixture. The latter is a tertiary eutectic mixture of biphenyl, orthoterphenyl and meta-terphenyl with a measured density of 1.063 gm/cm^3 at 40°C , the temperature at which this particular system was investigated. Table I shows the composition as given by the manufacturer, Monsanto Chemical Co., St. Louis, Missouri. Cross section and age information was obtained from the data book No. AT-1⁽⁴⁾. Measurements with this moderator were only carried out with 1.3 and 3 per cent enriched fuels. Lattice configurations are shown in Figure 9, with a lattice pitch of 2.032 cm.

TABLE I
Fuel Element Data

Enrichment w/o	Active dia. in cm	Active length (cm)	Gm/Rod U ²³⁵	Gm/cm ³ U ²³⁵	CLAD		Remarks	
					Material	O.D. cm		Walls cm
1.3	1.27	122	~17.7	0.1145	2-S Al	1.44	0.088	Sintered UO ₂ pellets
1.6	1.27	122	~21.8	0.1410	2-S Al	1.44	0.088	" " "
3.0	1.13	185	~42.7	0.2300	304 SS	1.27	0.071	" " "
93.2	1.27	122	~20.8	0.1344	2-S Al	1.44	0.088	U-Al alloy

TABLE II
Organic Moderator Composition

<u>Compound</u>	<u>Formula</u>	<u>Molecular Wt.</u>	<u>Liquid Eutectic Composition (molecular %)</u>
biphenyl	C ₁₂ H ₁₀	154.2	30.9
ortho-terphenyl	C ₁₈ H ₁₄	230.3	47.5
meta-terphenyl	C ₁₈ H ₁₄	230.3	21.6

In all three lattices (1.3%, 3%, and 93.2%) the graphite system is in reality a graphite test region containing ninety-four fuel rods arranged on a 5.080 cm pitch. The test region is contained in a watertight 6061-T6 aluminum can of 0.318 cm wall thickness and 61.60 cm diameter, mounted on the vertical axis of the reactor tank and resting on the bottom of the latter, held down by its own weight and that of the fuel.

Graphite discs, about 2 inches thick, stacked vertically to the desired height (which remained constant throughout the experiments) fill this can. Symmetrically placed on one centerline of the plane view are two full length holes of 2.0 inch diameter to accommodate the control rods (2.0 inch diameter, slabs 2 inches wide, and angles) to be measured. Graphite plugs with a 0.5 inch diameter hole are stacked into the 2 inch diameter holes to assure rigid geometry in the case of the 0.5 inch diameter cadmium control rods. Also provided is a .5 inch x 10 inch central slot to allow for the large control slabs of 10 inch width to be inserted. With the exception of the last mentioned slabs, all control rod arrays were pairs, in the graphite core, for symmetry reasons. Density of the AGOT graphite is 1.70 gm/cm³.

A water moderated driver region, loaded with fuel rods of 1.3 and 1.6 per cent enrichment, with a lattice pitch of 2.032 cm, surrounds the graphite test section. Again, reactivity is controlled by the surrounding water height. Figure 2 is a photograph of this system.

Measurements performed in the heavy water moderated cores include all three lattices, the lattice pitch being 4.064 cm, twice that of the light water and organic systems. To reduce the absorption of light water from the air, the reactor tank was sealed off with polyethylene sheets, leaving only small openings in places where the control rods were inserted. The heavy water was stored in a large underground dump tank, from which it was pumped into the reactor vessel. An air conditioning system kept the moderator and core temperatures as well as humidity constant and in equilibrium at 20°C. Samples of heavy water were taken out in intervals throughout the experiment and analyzed by the analytical chemistry group at Vallecitos. Information listed in Table III below represents averages of all samples examined. No significant deviations, outside the experimental errors in the analyses, were detected between the individual samples tested. Lattice diagrams are given in Figs. 7, 8a, b, c, d.

TABLE III

D₂O Analysis (20°C)

Specific Conductivity (micromhos)	12.3
Turbidity, Equivalent SiO ₂ (ppm)	1.5
Total Solids (ppm)	16.0
Mercury (ppm)	0.002
Chloride (ppm)	0.43
KmnO ₄ Demand (ppm)	3.0
Gross Beta Activity Excluding Tritium Activity (μc/ml)	1.1×10^{-6}
Gross Alpha Activity (μc/ml)	1.0×10^{-9}
Specific Gravity 20°C/ 20°C	1.10307
Light Water Content in (%)	4.5 ± 0.2

Finally, experiments in the light water moderated systems were carried out with all three enrichments. The moderator temperature is again 20°C. The lattice pitch is 2.032 cm. Lattice diagrams are shown in Figs. 4, 5, 6a, b, c, d.

It should be noted that in all eleven lattices the vertical distance from the bottom of the core containing vessel to the active core boundary was always 6.61 inches. Figure 3 is a vertical cross section of the assembly.

B. CONTROL RODS

All control rods studied were either slabs of various widths or cylinders of a number of diameters. Absorber materials examined were cadmium, silver, boron, and dysprosium; boron as boron-carbide (B_4C) and as an oxide (B_2O_3), dysprosium as Dy_2O_3 . A boron-carbide dispersion in solid aluminum, commercial boral, was also measured as well as combinations of silver and cadmium, and boron-carbide and dysprosium-oxide.

Complete design details of all control rods are given in Figures 11 to 21. An epoxy resin was sprayed on every rod in several thin layers to prevent any reactions with the moderators. A control rod drive mounted above the reactor tank provided accurate remote positioning of the inserted rods. Poison rods were measured individually as well as in pairs and symmetric arrays of 3×3 and 5×5 , depending on the physical dimensions of the core lattices. The lower active absorber region was always level with the bottom boundary of the active core.

The one inch diameter cadmium rod was, in reality, a hollow tube into which moderator could be filled. This arrangement is also known as a flux trap for apparent reasons, and its details can be seen on Figure 18.

Table IV lists the concentrations of the various absorbers examined. These data were obtained from either the manufacturer or the "Handbook of Chemistry and Physics".

TABLE IV
Densities of Control Rod Materials

Cd	8.67 gm/cm ³ (Chemical Rubber Handbook)
Ag	10.6 gm/cm ³ (Chemical Rubber Handbook)
B ₄ C	1.81 gm/cm ³ (Chemical Rubber Handbook)
B ₂ O ₃	1.82 gm/cm ³ (GE-APED, San Jose)
Dy ₂ O ₃	2.66 gm/cm ³ (GE-APED, San Jose)

Boral	$N_B = 0.0261 \frac{\text{atoms}}{\text{bn-cm}}$	These number densities are homogenized and include the Al-cladding. Information furnished by Brooks and Perkins Co., Detroit, Michigan.
	$N_C = 0.0065 \frac{\text{atoms}}{\text{bn-cm}}$	
	$N_{Al} = 0.0448 \frac{\text{atoms}}{\text{bn-cm}}$	

C. PULSED NEUTRON SOURCE AND DETECTOR SYSTEM

To decide upon the best method of measuring the nuclear worth of control rods in a reactor an experiment was performed to intercompare several known techniques⁽³⁾. The results favored the pulsed neutron source method as having the desirable range of application for our particular task. The validity of this technique for reactivity measurements has been demonstrated by other investigators⁽⁵⁾. As a consequence, a pulsed neutron generator of the OMNITRON type was built here by the Experimental Reactor Physics group.

The first use of a pulsed burst of neutrons was reported by Alvarez⁽⁶⁾ who used the Berkeley 36 inch cyclotron as a pulsed accelerator. Since then, various techniques have been developed, along with special equipment

such as time analyzers. A fairly recent (October, 1960) publication by Beckurts⁽⁷⁾ gives a general picture of the over-all status of reactor physics research with pulsed neutron source.

The OMNITRON is a one-stage linear accelerator, the accelerator tube of which is shown in Figure 22. Deuterons, ionized inside the center-electrode are accelerated to about 130-150 kev by a positive high voltage pulse of about 2 microseconds duration applied to the center electrode. The target bombarded with these deuterons contains adsorbed tritium (H^3) and a burst of neutrons of approximately 14.3 mev is obtained from the $H^3(d,n)He$ reaction. Source strength is about 5×10^6 neutrons per burst and repetition rates can be varied from 1 to 100 per second. At lower than the mentioned pulse rates, this particular type of source is difficult to monitor. In its place a KAMAN PULSATRON, model NT-60-8, built by Kaman Nuclear, Colorado Springs, Colorado, was used whenever conditions required low pulse rates. The source intensity is comparable to that of the OMNITRON, just described. For a continuous duty cycle the Pulsatron is limited to a repetition rate of three per second or less. Here again the neutrons result from the (d,n) reaction.

Figure 23 is a block diagram of the experimental apparatus and data analysis system. The firing sequence of both neutron generators is controlled by a time-multichannel analyzer, built by Technical Measurement Corporation, Northhaven, Connecticut, (model CN-110 digital computer plus No. 212 logic unit). This analyzer is a fully transistorized device, consisting essentially of a 16-binary scaler for buffer storage of incoming signals, a ferrite-core magnetic memory with a storage capacity of 256 words of 16 binary bits each, and appropriate switching circuitry. Analogue display of the memory contents is provided via built-in oscilloscope.

The 256 memory addresses in this analyzer are sequentially sensitized to become time channels with a 1,048,575 count capacity. Of these 256 channels, 255 are of equal duration T, adjustable from 10 to 2560

microseconds in factor steps of 2. The width of the remaining so-called pre-burst background channel is independently variable as $2^n \cdot T$ with $n = 1, \dots, 8$. The channel width is set by a 100 kc-crystal oscillator with a specified accuracy of ± 0.02 per cent from 0 to 50°C .

The analyzer has a time resolution of about 80 milli-microseconds for registering detector pulses in buffer storage. This resolving time is specifically that of a pulse shaping trigger circuit at the entrance of buffer storage. All "read and write" operations between buffer and memory are relegated to a 10 microsecond dead time interval separating end and beginning of successive channels.

For initiating a reactor pulsing sequence, an external triggering signal is supplied to the analyzer from the repetition rate generator. The pre-burst background channel is immediately sensitized and, upon closing, provides an output signal from the analyzer, which fires the neutron source.

Next, prior to the opening of the first data channel, the analyzer generates a time delay of duration $2^n \cdot T$ with $n = 1, \dots, 8$. All of the data channels then open in succession, whereupon the entire pulsing sequence is ended until another triggering signal is supplied by the repetition rate generator. The analyzer circuit prevents overlapping of sweep-time with the repetition period.

Data are extracted from the memory by a coupled Monroe printer and punch tape combination in a format that is read by a Philco 2000 Transac Computer via a data transmission system⁽¹¹⁾.

Reduction of taped data by the computer is carried out in accordance with a special program based upon the curve-fitting formulas of Behrens⁽¹²⁾. Appropriate corrections for counting rate losses are also computed.

A $\text{Li}^6\text{I}(\text{Eu})$ crystal, 1.0 mm thick and 2 inches in diameter, was used as scintillation detector of the thermal neutrons. While this crystal is

also sensitive to gamma rays from the decaying fission products, the pulses caused by neutrons are so much larger that they are easily separated from the gamma pulses provided the pile-up of the latter can be neglected. This is the case in all experiments to be described in this report. A CBS-7817 photomultiplier is used. A transistorized emitter-follower preamplifier, two cascaded Hewlett-Packard 460 AR linear amplifiers, and a pulse inverter (to positive) together with the time analyzer scaler completes the detector circuit. The inverter amplifier is necessary in the present arrangement since the analyzer does only accept positive input signals. Total resolving time is 0.7 microseconds, as determined experimentally by the multiple-source method⁽⁸⁾.

Characteristic reactor pulsing data, acquired with the equipment just described are depicted in Figure 24. Data are accumulated by pulsing the reactor repeatedly until the desired number of counts is collected as determined by counting statistics.

A typical experiment began with a flux profile measurement on the vertical and horizontal axis of symmetry of the clean, basic core. After a short, low power run with the particular basic lattice configuration at critical, a fuel element gamma scan was performed with a discriminator base-line setting of ~ 0.6 mev. The location of highest activity was determined on the center element of the lattice and a scan made in the horizontal plane at this height, which generally corresponded to approximately one-half the active core height. The center fuel element scan, of course, provided the flux profile on the vertical axis. Figures 25 to 43 represent the relative thermal flux distributions in the various basic lattices.

The pulsed neutron source target was placed against one of the active core faces, therefore in the moderator, at about $1/4$ of the core height, as indicated in Figure 44. To reduce the delay time after the burst by assuring modal purity, detector position dependence of alpha was examined by comparing results as a function of the angle between detector and source in the horizontal and vertical plane with the reactor about $\$1$ subcritical. With the exception of the heavy water moderated lattices, the decay constants were found to be independent of position as long as the detector was mounted close to the center of a reactor face.

To find the decay constant α_c at delayed critical, a number of alphas were measured as a function of moderator height with no control rods inserted. From a plot of α vs. ΔB^2 , α_c can be found by extrapolation, assuming $\alpha \approx \alpha_c + m\Delta B^2$, which is a good approximation close to critical. We define $\Delta B^2_c = B_h^2 - B_c^2$, B_c^2 being the delayed critical buckling.

Another method used to measure α_c was to render the reactor a few cents, say 2-3¢, subcritical, as determined by period measurements and the inhour equation, and then pulse it at this particular moderator height. From the relationship $\rho(\$/) = \frac{\alpha}{\alpha_c} - 1$, relating the reactivity in dollars to the prompt fundamental decay constant near delayed critical, α_c is found. The delayed critical decay constants are tabulated in Table V; both values of α_c are shown for those cases where both methods were applied.

To measure the decay constants of the various control rods in a particular core lattice, the critical moderator height was first determined by interpolation of two period measurements, one positive and one negative. The control rod was then inserted such that the lower poison region boundary was on the same level with the bottom fuel plane. With the moderator height remaining at just critical, the pulse operation was initiated and data accumulated. Continuous data display on the analyzer oscilloscope conveniently allowed observation of the experimental progress. The average background was determined from those channels immediately following the decay of the prompt neutron pulse. This post-burst background differs from the pre-burst background, as measured in the analyzer background channel (i.e., No. 1) only near critical when repetition rates are very slow. The post-burst background gives, in general, a better estimate of the slowly varying background which exists during the prompt neutron pulse decay.

The ratio of the peak neutron density during the propagation of the burst, to the source induced background is given as

$$1 + \frac{[1 - k_{\text{eff}} (1 - \beta)]^2 \frac{1}{R}}{2\beta (1 - \beta) k_{\text{eff}} \ell}$$

where R is the source repetition rate and ℓ is the generation time of the prompt neutrons. It is, of course, desirable to keep this signal-to-noise ratio as high as possible and it is done by choosing a reasonably low pulse rate.

A problem arising in the heavy water moderated lattices is that of photo-neutrons produced in the moderator by the gamma activity from fission products⁽⁹⁾. H. T. Williams⁽¹⁰⁾ calculated a total effective delayed fraction of $\sum \beta_i = 0.00783$ including (γ, n) 's, $i = 1, 2, \dots, 13$. After 29 minutes all delayed (γ, n) 's practically would have reached saturation values, except for the three longest periods (76, 63, and 2.4 hours). The k_{eff} of this system would then be about $k(t = 29 \text{ min}) \approx 1.000043$, with the period being about $T \approx 1.6$ hours. This means that over the 28 min. interval the power would have increased over the initial value by a factor of 1.3. Williams' calculations were confirmed by our observations as it took, in these systems, approximately 30 minutes after start-up for the reactor to stabilize so that the critical moderator height could be determined accurately.

Some changes in the lattice configuration of a number of basic cores were necessary to make possible the insertion of certain control rods to be measured. These changes are reflected in Figures 4 to 10. The remaining parts of the various lattices, not shown on all layouts, are equivalent to the basic core configurations given on the same figures.

PART II: RESULTS AND DISCUSSION

The prompt decay constants listed in Tables VI to IX, and graphically presented in Figures 50 to 60, were obtained by fitting a single exponential to the experimental data after count loss and background corrections were performed. Exceptions to this are the heavy water moderated lattices where it was necessary, in certain cases, when the prompt lifetime was relatively long and the burst repetition rate low, to deal with a sum of two exponentials. Least-square calculations were carried out on the IBM 704, 7090, and the Philco 2000, using the EXPLICIT code, which allows a choice of ten different analysis start-channels per problem, for both pre-burst and post-burst background analysis. Errors shown are those due to counting statistics only.

The moderator-to-fuel volume ratios are given on Figures 50 to 58.

Specifically, alpha values tabulated in Tables VI to IX represent decay constants normalized to one value of the geometrical buckling; the latter is given at the foot of each table. Certain changes in the basic lattice configurations to accommodate control rods caused a change in the critical buckling. The buckling to which the alphas were normalized corresponds to a mean value of the particular lattice.

Raw data are given with the corresponding physical moderator heights in Table X to XIII. Normalization was performed in the region where $\alpha = \alpha_c + m\Delta B^2$ is a good approximation as established by measurement. The slope m is determined from alpha vs. moderator height measurements as in Figures 45 to 49, with α_c representing the prompt decay constant at delayed critical. Kloverstrom and Komoto⁽⁵⁾ have measured α versus geometrical buckling with control rods "in" and "out" of the core for a number of moderator-to-fuel ratios (301, 603, 1206, 2355) and found only small differences between the respective slopes of the rod "in" and "out" cases. It thus appears justified to carry out normalizations of the alphas in the manner just described, with the slope m determined from the clean core measurements rather than from the poisoned ones, without introducing significant errors.

In order to obtain the geometrical bucklings along the Z-axis (vertical), the vertical reflector savings δ were measured in the usual manner by fitting a cosine function of the form

$$y = A \cos \frac{\pi (Z - D)}{L}$$

to the corresponding in-core flux profile in the region not less than two diffusion lengths away from the core-reflector boundaries. Values for savings are given in Table V, together with the α_c 's. The vertical savings is due to the bottom reflector and the non-moderated fuel above the moderator level. Horizontal reflector savings were not measured. These horizontal savings do not enter in the α_c determination from Figures 45 to 49, because the buckling changes, ΔB^2 , are due to variations in the moderator height only. Specifically,

$$\frac{\Delta B^2}{\pi^2} = \frac{1}{(h + \delta)^2} - \frac{1}{(h_c + \delta)^2}$$

where h_c is the critical moderator height measured from the bottom fuel plane and δ is the experimentally determined vertical savings just mentioned. The critical moderator heights listed in Tables X to XIII are accurate to within ± 0.01 cm and do not include δ nor the extrapolation length.

We have so far not mentioned nuclear worth or reactivity equivalent of control rods in terms of the prompt decay constants. It may be useful, however, in certain applications, to consider relative worth, i.e., relative to a standard rod; for instance, in the present case to the 0.5 inch diameter cadmium rod. The relative worth, R_x , of any control element or combination thereof can simply be found by the relationship

$$R_x = \frac{\alpha_x - \alpha_c}{\alpha_{std} - \alpha_c} R_{std}$$

Here α_c is the delayed critical decay constant and R_{std} is the reactivity worth of the standard, usually taken as unity.

We have previously mentioned in Part I that, as a rule, no particular difficulties arose from higher modes in the prompt decay, even as far subcritical as β_{10} , regardless of whether subcriticality was achieved by a geometrical buckling change or insertion of a control rod. However, the heavy water moderated lattices proved to be an exception to this. In certain control rod cases it was found that at only β_6 subcritical, the second mode decayed only twice as fast as the fundamental, thus requiring long delay times after the initial bursts. As a consequence, count rates were low by the time the decay was a pure modal one and data accumulation time increased considerably.

The clearest advantage of the pulsed source method is that a purely normal mode distribution exists shortly after the pulse and hence one can follow the lowest decay constant α after the transients are gone. This fact is also true for the leakage neutrons, i.e., every point in the entire system, reflector included, has the same time behavior in the normal mode situation. The leakage neutrons in the reflector, therefore, are a proper measure of the interior behavior.

TABLE V

Delayed Critical Decay Constants and Vertical Reflector Savings

Moderator	% Enrichment	α_c (sec ⁻¹)		δ (cm)
		Extrapolated	Direct Meas.	
H ₂ O	1.3	130 ± 2.5	--	14
	3.0	182 ± 2	--	14
	93.2	120 ± 2	120 ± 0.5	14
D ₂ O	1.3	17 ± 1	---	28
	3.0	22 ± 2	20 ± 0.2	23
	93.2	12 ± 1	12.5 ± 0.05	16.5
Graphite	1.3	85 ± 4	--	25
	3.0	90 ± 2.5	89 ± 0.5	27.5
	93.2	58 ± 2	58 ± 0.2	26.5
Organic	1.3	128 ± 2	--	14
	3.0	176 ± 2	--	14

TABLE VI

Normalized Alpha Values for H_2O Moderated Lattices

Control Rod Configuration	α in sec^{-1}		
	1.3%	3%	93.2%
.5" dia. Cd-Rod	186 ± 6	390 ± 3	376 ± 1
2" wide Cd-Slab	260 ± 4	572 ± 3	540 ± 5
2" wide Boral-Slab	- - -	667 ± 3	667 ± 2
Boral-Angle	- - -	761 ± 4	775 ± 4
Cd-Angle	301 ± 10	- - -	588 ± 2
1" dia. B_4C -Rod	329 ± 13	701 ± 4	761 ± 6
1" dia. Dy_2O_3 -Rod	300 ± 4	584 ± 3	636 ± 6
1" dia. Dy_2O_3 + B_4C -Rod	322 ± 6	620 ± 3	677 ± 3
1" dia. Cd-Tube (empty)	275 ± 10	489 ± 3	530 ± 2
1" dia. Cd-Tube (filled)	303 ± 13	552 ± 3	594 ± 2
2" dia. Cd-Annulus (filled)	$433 \pm 18^*$	$862 \pm 3^*$	860 ± 8
10" wide Cd-Slab	$778 \pm 6^*$	$1459 \pm 13^*$	1733 ± 14
10" wide Ag + Cd-Slab	$851 \pm 20^*$	$1601 \pm 11^*$	1978 ± 25
10" wide B_2O_3 -Slab	$854 \pm 10^*$	$1011 \pm 7^*$	- - -
.5" dia. Cd-Rod, Pair	247 ± 3	460 ± 3	445 ± 2
2" wide Cd-Slab, Pair	420 ± 5	770 ± 4	650 ± 3
2" wide Boral-Slab, Pair	- - -	938 ± 7	824 ± 3
Boral-Angle, Pair	- - -	1050 ± 9	946 ± 8
Cd-Angle, Pair	438 ± 5	- - -	680 ± 3
2" dia. Cd-Annulus, Pair(filled)	- - -	- - -	1030 ± 5
2" dia. Cd-Rods, 3x3 Array	- - -	1289 ± 9	1363 ± 6
2" wide Cd-Slabs, 3x3 Array	- - -	1974 ± 32	2414 ± 17
2" wide Boral-Slabs, 3x3 Array	- - -	2259 ± 32	2750 ± 34
.5" dia. Cd-Rods, 5x5 Array	1479 ± 54	- - -	- - -
2" wide Cd-Slabs, 5x5 Array	2129 ± 185	- - -	- - -
2" wide Boral-Slabs, 5x5 Array	- - -	- - -	- - -
B_z^2 in units of 10^{-4} cm^{-2}	8.220	9.922	6.502
B_z^2 for alphas marked with asterisk	6.980	7.203	

Errors given are those due to counting statistics only.

TABLE VII

Normalized Alpha Values for D₂O Moderated Lattices

Control Rod Configuration	α in sec ⁻¹		
	1.3%	3%	93.2%
.5" dia. Cd-Rod	45 ± 0.1	64 ± 0.2	68 ± 0.1
2" wide Cd-Slab	79 ± 0.2	97 ± 0.5	118 ± 0.5
2" wide Boral-Slab	87 ± 0.2	121 ± 0.3	146 ± 0.5
Boral-Angle	96 ± 0.2	133 ± 0.5	160 ± 1
Cd-Angle	78 ± 0.2	- - -	128 ± 0.5
1" dia. B ₄ C-Rod	97 ± 0.2	139 ± 0.5	160 ± 0.3
1" dia. Dy ₂ O ₃ -Rod	84 ± 0.2	116 ± 0.3	134 ± 0.3
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	90 ± 0.4	123 ± 0.3	144 ± 0.2
1" dia. Cd-Tube (empty)	73 ± 0.2	94 ± 0.2	116 ± 0.5
1" dia. Cd-Tube (filled)	72 ± 0.2	96 ± 0.3	117 ± 0.2
2" dia. Cd-Annulus (filled)	117 ± 0.2	159 ± 0.6	176 ± 0.5
10" wide Cd-Slab	205 ± 0.5	258 ± 2	325 ± 2
10" wide Ag + Cd-Slab	219 ± 0.3	271 ± 2	340 ± 2
10" wide B ₂ O ₃ -Slab	225 ± 1.5	238 ± 2	- - -
.5" dia. Cd-Rod, Pair	75 ± 0.5	92 ± 0.2	108 ± 0.2
2" wide Cd-Slab, Pair	124 ± 0.3	148 ± 0.5	190 ± 0.5
2" wide Boral-Slab, Pair	148 ± 0.3	190 ± 1	232 ± 1
Boral-Angle, Pair	164 ± 0.4	208 ± 2	251 ± 1
Cd-Angle, Pair	135 ± 0.3	- - -	207 ± 0.5
2" dia. Cd-Annulus, Pair (filled)	180 ± 0.4	240 ± 2	278 ± 0.5
.5" dia. Cd-Rods, 3x3 Array	- - -	- - -	302 ± 2
2" wide Cd-Slabs, 3x3 Array	- - -	- - -	436 ± 7
2" wide Boral-Slabs, 3x3 Array	- - -	- - -	466 ± 8
.5" dia. Cd-Rods, 5x5 Array	353 ± 1	385 ± 4	- - -
2" wide Cd-Slabs, 5x5 Array	424 ± 12	453 ± 9	- - -
2" wide Boral-Slabs, 5x5 Array	451 ± 8	417 ± 5	- - -
B ₂ in units of 10 ⁻⁴ cm ⁻²	4.625	4.297	5.466

Errors given are those due to counting statistics only.

TABLE VIII

Normalized Alpha Values for Graphite Moderated Lattices

Control Rod Configuration	α in sec ⁻¹		
	1.3%	3%	93.2%
10" wide Cd-Slab	242 $\pm$ 4	282 $\pm$ 1	394 $\pm$ 2
10" wide Ag + Cd-Slab	292 $\pm$ 3	320 $\pm$ 2	459 $\pm$ 3
10" wide B ₂ O ₃ -Slab	317 $\pm$ 3	342 $\pm$ 1	482 $\pm$ 4
.5" dia. Cd-Rod, Pair	129 $\pm$ 2	137 $\pm$ 0.5	147 $\pm$ 1
2" wide Cd-Slab, Pair	228 $\pm$ 4	194 $\pm$ 2	234 $\pm$ 1
2" wide Boral-Slab, Pair	226 $\pm$ 2	242 $\pm$ 2	311 $\pm$ 2
Boral-Angle, Pair	220 $\pm$ 4	261 $\pm$ 1	334 $\pm$ 2
Cd-Angle, Pair	223 $\pm$ 5	207 $\pm$ 0.5	251 $\pm$ 1
2" dia. Cd-Annulus, Pair(filled)	271 $\pm$ 3	236 $\pm$ 1	303 $\pm$ 1
B ₂ ² in units of 10 ⁻⁴ cm ⁻²	5.095	5.060	4.676

Errors given are those due to counting statistics only.

TABLE IX

Normalized Alpha Values for Organic Moderated Lattices

Control Rod Configuration	α in sec ⁻¹	
	1.3%	3%
.5" dia. Cd-Rod	195 ± 1	313 ± 1
2" wide Cd-Slab	255 ± 2	453 ± 4
2" wide Boral-Slab	305 ± 2	554 ± 3
Boral-Angle	328 ± 2	623 ± 4
Cd-Angle	271 ± 2	- - -
1" dia. B ₄ C-Rod	329 ± 2	618 ± 4
1" dia. Dy ₂ O ₃ -Rod	275 ± 2	510 ± 2
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	300 ± 2	548 ± 4
1" dia. Cd-Tube (empty)	240 ± 1	422 ± 2
1" dia. Cd-Tube (filled)	265 ± 2	460 ± 2
2" dia. Cd-Annulus (filled)	- - -	810 ± 4
10" wide Cd-Slab	638 ± 6	1253 ± 11
10" wide Ag + Cd-Slab	693 ± 5	1399 ± 12
10" wide B ₂ O ₃ -Slab	713 ± 5	943 ± 8
.5" dia. Cd-Rod, Pair	239 ± 1	412 ± 2
2" wide Cd-Slab, Pair	346 ± 3	632 ± 3
2" wide Boral-Slab, Pair	421 ± 3	803 ± 4
Boral-Angle, Pair	480 ± 3	887 ± 6
Cd-Angle, Pair	378 ± 2	- - -
2" dia. Cd-Annulus, Pair(filled)	590 ± 3	1212 ± 13
.5" dia. Cd-Rods, 3x3 Array	- - -	1017 ± 7
2" wide Cd-Slabs, 3x3 Array	- - -	1500 ± 17
2" wide Boral-Slabs, 3x3 Array	- - -	1768 ± 19
.5" dia. Cd-Rods, 5x5 Array	1059 ± 15	- - -
2" wide Cd-Slabs, 5x5 Array	1439 ± 25	- - -
2" wide Boral-Slabs, 5x5 Array	1617 ± 32	- - -
B _Z ² in units of 10 ⁻⁴ cm ⁻²	6.431	7.812

Errors given are those due to counting statistics only.

TABLE X-A
Measured Alpha Values for H₂O, 1.3% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$		
			α	$\pm$	$\Delta\alpha$
.5" dia. Cd-Rod	4-A	91.10	233	± 6	
2" wide Cd-Slab	4-B	93.21	280	± 4	
2" wide Boral-Slab		---	---		
Boral-Angle		---	---		
Cd-Angle	4-C	93.28	321	± 10	
1" dia. B ₄ C-Rod	4-A	91.10	376	± 13	
1" dia. Dy ₂ O ₃ -Rod	4-A	91.10	320	± 4	
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	4-A	91.10	342	± 6	
1" dia. Cd-Tube (empty)	4-A	91.10	295	± 10	
1" dia. Cd-Tube (filled)	4-A	91.10	323	± 13	
2" dia. Cd-Annulus (filled)	4-E	106.03	417	± 18	
10" wide Cd-Slab	4-F	104.25	778	± 6	
10" wide Ag + Cd-Slab	4-F	104.25	851	± 20	
10" wide B ₂ O ₃ -Slab	4-F	104.25	854	± 10	
.5" dia. Cd-Rod, Pair	4-I	91.39	290	± 3	
2" wide Cd-Slab, Pair	4-H	94.92	420	± 5	
2" wide Boral-Slab, Pair		---	---		
Boral-Angle, Pair		---	---		
Cd-Angle, Pair	4-J	95.17	435	± 5	
2" dia. Cd-Annulus Pair(filled)	4-G	129.71	731		
.5" dia. Cd-Rods, 5x5 Array	4-K	99.89	1425	± 54	
2" wide Cd-Slabs, 5x5 Array	4(Basic)*	90.40	2185	± 185	
2" wide Boral-Slabs, 5x5 Array		---	---		

* Rod distribution similar to Fig. 8d

TABLE X-B
Measured Alpha Values for H₂O, 3% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$		
			α	$\pm$	$\Delta\alpha$
.5" dia. Cd-Rod	4-A	85.08	390	± 3	
2" wide Cd-Slab	4-B	87.67	520	± 3	
2" wide Boral-Slab	4-B	87.67	615	± 3	
Boral-Angle	4-C	88.10	701	± 4	
Cd-Angle		---	---		
1" dia. B ₄ C-Rod	4-A	85.08	701	± 4	
1" dia. Dy ₂ O ₃ -Rod	4-A	85.08	584	± 3	
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	4-A	85.08	620	± 3	
1" dia. Cd-Tube (empty)	4-A	85.08	489	± 3	
1" dia. Cd-Tube (filled)	4-A	85.08	552	± 3	
2" dia. Cd-Annulus (filled)	4-E	108.67	786	± 3	
10" wide Cd-Slab	4-F	102.40	1459	± 13	
10" wide Ag + Cd-Slab	4-F	102.40	1601	± 11	
10" wide B ₂ O ₃ -Slab	4-F	102.40	1011	± 7	
.5" dia. Cd-Rod, Pair	4-I	85.57	450	± 3	
2" wide Cd-Slab, Pair	4-H	89.54	686	± 4	
2" wide Boral-Slab, Pair	4-H	89.54	854	± 7	
Boral-Angle, Pair	4-J	89.54	966	± 9	
Cd-Angle, Pair		---	---		
2" dia. Cd-Annulus Pair(filled)	4-G	135.01	1223		
2" dia. Cd-Rods, 3x3 Array	4-K*	88.75	1216	± 9	
2" wide Cd-Slabs, 3x3 Array	5 **	84.31	1990	± 32	
2" wide Boral-Slabs, 3x3 Array	5 **	84.31	2275	± 32	

* See note on Fig. 4

** Rod distribution same as Fig. 8d.

TABLE X-C
Measured Alpha Values for H₂O, 93.2% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$		
			α	$\pm$	$\Delta\alpha$
.5" dia. Cd-Rod	6d	110.75	366	± 1	
2" wide Cd-Slab	6d	102.88	583	± 5	
2" wide Boral-Slab	6d	102.88	710	± 2	
Boral-Angle	6c	103.90	810	± 4	
Cd-Angle	6c	103.90	623	± 2	
1" dia. B ₄ C-Rod	6c	109.14	761	± 6	
1" dia. Dy ₂ O ₃ -Rod	6c	109.14	636	± 6	
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	6c	109.14	677	± 3	
1" dia. Cd-Tube (empty)	6c	109.14	530	± 2	
1" dia. Cd-Tube (filled)	6c	109.14	594	± 2	
2" dia. Cd-Annulus (filled)	6c	104.46	891	± 8	
10" wide Cd-Slab	6d	107.14	1720	± 14	
10" wide Ag + Cd-Slab	6d	107.14	1965	± 25	
10" wide B ₂ O ₃ -Slab		---	---		
.5" dia. Cd-Rod, Pair		111.21	432	± 2	
2" wide Cd-Slab, Pair	6a	105.80	672	± 3	
2" wide Boral-Slab, Pair	6a	105.80	846	± 3	
Boral-Angle, Pair	6b	105.98	967	± 8	
Cd-Angle, Pair	6b	105.98	701	± 3	
2" dia. Cd-Annulus Pair(filled)	6b	102.62	1075	± 5	
2" dia. Cd-Rods, 3x3 Array	6a	110.95	1352	± 6	
2" wide Cd-Slabs, 3x3 Array	6a(Basic)*	106.88	2428	± 17	
2" wide Boral-Slabs, 3x3 Array	6a(Basic)*	106.92	2764	± 34	

* Rod distribution same as Fig. 8d.

TABLE XI-A

Measured Alpha Values for D₂O, 1.3% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$		
			α	$\pm$	$\Delta\alpha$
.5" dia. Cd-Rod	7(Basic)*	114.30	45	± 0.1	
2" wide Cd-Slab	7(Basic)*	114.30	79	± 0.2	
2" wide Boral-Slab	7(Basic)*	114.30	87	± 0.2	
Boral-Angle	7(Basic)*	114.30	96	± 0.2	
Cd-Angle	7(Basic)*	114.30	78	± 0.2	
1" dia. B ₄ C-Rod	7(Basic)*	114.30	97	± 0.2	
1" dia. Dy ₂ O ₃ -Rod	7(Basic)*	114.30	84	± 0.2	
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	7(Basic)*	114.30	90	± 0.4	
1" dia. Cd-Tube (empty)	7(Basic)*	114.30	73	± 0.2	
1" dia. Cd-Tube (filled)	7(Basic)*	114.30	72	± 0.2	
2" dia. Cd-Annulus (filled)	7-A	114.42	117	± 0.2	
10" wide Cd-Slab	7(Basic)*	114.42	205	± 0.5	
10" wide Ag + Cd-Slab	7(Basic)*	114.42	219	± 0.3	
10" wide B ₂ O ₃ -Slab	7(Basic)*	114.25	225	± 1.5	
.5" dia. Cd-Rod, Pair	7(Basic)*	114.42	75	± 0.5	
2" wide Cd-Slab, Pair	7(Basic)*	114.42	124	± 0.5	
2" wide Boral-Slab, Pair	7(Basic)*	114.42	148	± 3	
Boral-Angle, Pair	7-B	114.33	164	± 0.4	
Cd-Angle, Pair	7-B	114.33	135	± 0.3	
2" dia. Cd-Annulus, Pair(filled)	7-C	114.23	180	± 0.4	
.5" dia. Cd-Rods, 5x5 Array	7-D	114.20	353	± 1	
2" wide Cd-Slabs, 5x5 Array	7(Basic)**	114.53	424	± 12	
2" wide Boral-Slabs, 5x5 Array	7(Basic)**	114.50	450	± 8	

* Rod distribution same as D₂O, 93.2%

** Rod distribution similar to Fig. 8d.

TABLE XI-B
Measured Alpha Values for D₂O, 3% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$		
			α	$\pm$	$\Delta\alpha$
.5" dia. Cd-Rod	7(Basic)*	124.98	64	± 0.2	
2" wide Cd-Slab	7(Basic)*	124.98	97	± 0.5	
2" wide Boral-Slab	7(Basic)*	124.98	121	± 0.3	
Boral-Angle	7(Basic)*	124.98	133	± 0.5	
Cd-Angle		---	---		
1" dia. B ₄ C-Rod	7(Basic)*	124.98	139	± 0.5	
1" dia. Dy ₂ O ₃ -Rod	7(Basic)*	124.98	116	± 0.3	
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	7(Basic)*	124.98	123	± 0.3	
1" dia. Cd-Tube (empty)	7(Basic)*	124.98	94	± 0.2	
1" dia. Cd-Tube (filled)	7(Basic)*	124.98	96	± 0.3	
2" dia. Cd-Annulus (filled)	7-A	125.50	154	± 0.6	
10" wide Cd-Slab	7(Basic)*	124.98	258	± 2	
10" wide Ag + Cd-Slab	7(Basic)*	124.98	271	± 2	
10" wide B ₂ O ₃ -Slab	7(Basic)*	124.98	238	± 2	
.5" dia. Cd-Rod, Pair	7(Basic)*	124.98	92	± 0.2	
2" wide Cd-Slab, Pair	7(Basic)*	124.98	148	± 0.5	
2" wide Boral-Slab, Pair	7(Basic)*	124.98	190	± 1	
Boral-Angle, Pair	7-B	124.93	215	± 2	
Cd-Angle, Pair		---	---		
2" dia. Cd-Annulus Pair(filled)	7-C	125.12	234	± 2	
.5" dia. Cd-Rods, 5x5 Array	7-D	124.91	392	± 4	
2" wide Cd-Slabs, 5x5 Array	7(Basic)**	124.94	460	± 9	
2" wide Boral-Slabs, 5x5 Array	7(Basic)**	---	424	± 5	

* Rod distribution same as D₂O, 93.2%

** Rod distribution similar to Fig. 8a.

TABLE XI-C

Measured Alpha Values for D₂O, 93.2% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$		
			α	$\pm$	$\Delta\alpha$
.5" dia. Cd-Rod	8b	114.97	67	± 0.1	
2" wide Cd-Slab	8b	114.97	117	± 0.5	
2" wide Boral-Slab	8b	114.97	145	± 0.5	
Boral-Angle	8b	114.97	159	± 1	
Cd-Angle	8b	114.97	127	± 0.5	
1" dia. B ₄ C-Rod	8b	114.73	160	± 0.3	
1" dia. Dy ₂ O ₃ -Rod	8b	114.73	134	± 0.3	
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	8b	114.73	144	± 0.2	
1" dia. Cd-Tube (empty)	8b	114.73	116	± 0.5	
1" dia. Cd-Tube (filled)	8b	114.73	117	± 0.2	
2" dia. Cd-Annulus (filled)	8a (Basic)	113.31	180	± 0.5	
10" wide Cd-Slab	8c	114.73	325	± 2	
10" wide Ag + Cd-Slab	8c	114.73	340	± 2	
10" wide B ₂ O ₃ -Slab		---	---		
.5" dia. Cd-Rod, Pair	8c	114.97	107	± 0.2	
2" wide Cd-Slab, Pair	8c	114.97	189	± 0.5	
2" wide Boral-Slab, Pair	8c	114.97	231	± 1	
Boral-Angle, Pair	8c	114.73	251	± 1	
Cd-Angle, Pair	8c	114.73	207	± 0.5	
2" dia. Cd-Annulus Pair(filled)	8a(Basic)	113.43	282	± 0.5	
2" dia. Cd-Rods, 3x3 Array	8d	114.56	302	± 2	
2" wide Cd-Slabs, 3x3 Array	8d	114.56	436	± 7	
2" wide Boral-Slabs, 3x3 Array	8d	114.56	466	± 8	

TABLE XII-A

Measured Alpha Values for Graphite, 1.3% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$	
			α	$\pm \Delta\alpha$
10" wide Cd-Slab	9	111.40	248	± 4
10" wide Ag + Cd-Slab	9	111.40	298	± 3
10" wide B_2O_3 -Slab	9	111.40	323	± 3
.5" dia. Cd-Rod, Pair	9	111.00	138	± 2
2" wide Cd-Slab, Pair	9	112.53	228	± 4
2" wide Boral-Slab, Pair	9	112.53	226	± 2
Boral-Angle, Pair	9	112.53	220	± 4
Cd-Angle, Pair	9	112.53	223	± 5
2" dia. Cd-Annulus Pair, empty	9	112.53	271	± 3

TABLE XII-B

Measured Alpha Values for Graphite, 3% Fuel

10" wide Cd-Slab	9	111.98	282	± 1
10" wide Ag + Cd-Slab	9	111.98	320	± 2
10" wide B_2O_3 -Slab	9	111.94	342	± 1
.5" dia. Cd-Rod, Pair	9	111.98	137	± 0.5
2" wide Cd-Slab, Pair	9	113.45	185	± 2
2" wide Boral-Slab, Pair	9	113.40	233	± 2
Boral-Angle, Pair	9	113.35	252	± 1
Cd-Angle, Pair	9	113.38	198	± 0.5
2" dia. Cd-Annulus Pair, empty	9	113.38	227	± 1

TABLE XII-C

Measured Alpha Values for Graphite, 93.2% Fuel

10" wide Cd-Slab	9	119.46	390	± 2
10" wide Ag + Cd-Slab	9	119.46	455	± 3
10" wide B_2O_3 -Slab	9	119.46	478	± 4
.5" dia. Cd-Rod, Pair	9	119.46	143	± 1
2" wide Cd-Slab, Pair	9	118.63	234	± 1
2" wide Boral-Slab, Pair	9	118.63	311	± 2
Boral-Angle, Pair	9	118.63	334	± 2
Cd-Angle, Pair	9	118.63	251	± 1
2" dia. Cd-Annulus Pair, empty	9	118.63	303	± 1

TABLE XIII-A

Measured Alpha Values for Organic, 1.3% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$	
			α	$\pm \Delta\alpha$
.5" dia. Cd-Rod	4-A	108.38	195	± 1
2" wide Cd-Slab	4-B	108.03	257	± 2
2" wide Boral-Slab	4-B	108.17	306	± 2
Boral-Angle	4-C	108.17	329	± 2
Cd-Angle	4-C	108.10	272	± 2
1" dia. B_4C -Rod	4-A	108.38	329	± 2
1" dia. Dy_2O_3 -Rod	4-A	108.38	275	± 2
1" dia. $\text{Dy}_2\text{O}_3 + \text{B}_4\text{C}$ -Rod	4-A	108.38	300	± 2
1" dia. Cd-Tube (empty)	4-A	108.38	240	± 1
1" dia. Cd-Tube (filled)	4-A	108.38	265	± 2
2" dia. Cd-Annulus (filled)		---	---	
10" wide Cd-Slab	4-F	108.83	633	± 6
10" wide Ag + Cd-Slab	4-F	108.83	688	± 5
10" wide B_2O_3 -Slab	4-F	108.83	708	± 5
.5" dia. Cd-Rod, Pair	4-I	108.15	241	± 1
2" wide Cd-Slab, Pair	4-H	107.76	351	± 3
2" wide Boral-Slab, Pair	4-H	107.76	426	± 3
Boral-Angle, Pair	4-J	108.46	479	± 3
Cd-Angle, Pair	4-J	108.46	377	± 2
2" dia. Cd-Annulus Pair (filled)	4-G	112.92	551	± 3
.5" dia. Cd-Rods, 5x5 Array	4-K	103.32	1108	± 15
2" wide Cd-Slabs, 5x5 Array	10(Basic)*	108.76	1434	± 25
2" wide Boral-Slabs, 5x5 Array	10(Basic)*	108.76	1612	± 32

* Rod distribution similar to Fig. 8d.

TABLE XIII-B
Measured Alpha Values for Organic, 3% Fuel

Control Rod Configuration	Lattice Reference Fig. No.	Critical Mod. Ht. (cm)	$\alpha(\text{sec}^{-1})$
			$\alpha \pm \Delta\alpha$
.5" dia. Cd-Rod	4-A	95.86	342 $\pm$ 1
2" wide Cd-Slab	4-B	97.26	455 $\pm$ 4
2" wide Boral-Slab	4-B	97.26	556 $\pm$ 3
Boral-Angle	4-C	97.68	616 $\pm$ 4
Cd-Angle	4-C	---	---
1" dia. B ₄ C-Rod	4-A	97.32	618 $\pm$ 4
1" dia. Dy ₂ O ₃ -Rod	4-A	97.48	507 $\pm$ 2
1" dia. Dy ₂ O ₃ + B ₄ C-Rod	4-A	97.34	548 $\pm$ 4
1" dia. Cd-Tube (empty)	4-A	97.34	422 $\pm$ 2
1" dia. Cd-Tube (filled)	4-A	97.56	456 $\pm$ 2
2" dia. Cd-Annulus (filled)	4-A	101.75	729 $\pm$ 4
10" wide Cd-Slab	4-F	98.80	1239 $\pm$ 11
10" wide Ag + Cd-Slab	4-F	98.80	1385 $\pm$ 12
10" wide B ₂ O ₃ -Slab	4-F	98.80	929 $\pm$ 8
.5" dia. Cd-Rod, Pair	4-I	97.72	405 $\pm$ 2
2" wide Cd-Slab, Pair	4-H	97.77	624 $\pm$ 3
2" wide Boral-Slab, Pair	4-H	97.77	795 $\pm$ 4
Boral-Angle, Pair	4-J	97.85	877 $\pm$ 6
Cd-Angle, Pair	4-J	---	---
2" dia. Cd-Annulus Pair(filled)	4-G	104.68	1086 $\pm$ 13
2" dia. Cd-Rods, 3x3 Array	4-K*	96.62	1031 $\pm$ 7
2" wide Cd-Slabs, 3x3 Array	10(Basic)**	97.72	1493 $\pm$ 17
2" wide Boral-Slabs, 3x3 Array	10(Basic)**	97.72	1761 $\pm$ 19

* See note on Fig. 4

** Rod distribution same as Fig. 8d.

(Viewed From Above)

Figure 1. TYPICAL LATTICE WITH 2" DOUBLE SLAB AND SAFETY SHEETS INSERTED

Figure 2. GRAPHITE CORE WITH PERIPHERAL DRIVER ANNULUS, 10" CONTROL SLAB INSERTED IN CENTER SLOT

(Scale: 2cm = 1 ft.)

Figure 3. CORE ASSEMBLY, VERTICAL CROSS SECTION

Basic Core: Rectangular parallelepiped with 35×35 square array of fuel elements.

Figure 4. LATTICE CONFIGURATIONS, H₂O, 1.3% FUEL

Basic Core:

$$M_c = 377 + (2)(72) + (4)(6) = 545 \text{ Elements}$$

$$H_c = 84.08 \text{ cm}$$

$$\text{Lattice Pitch: } 2.032 \text{ cm}$$

Note:

Lattice modifications to accommodate control rods are equivalent to those of the H_2O , 1.3% core, Fig. 4, except for H_2O-K , where only 9 elements were removed.

Figure 5. LATTICE CONFIGURATIONS, H_2O , 3% FUEL

Basic Core

$$\begin{aligned}
 M_c &= (15 \times 15) + 4(3) - 4 \\
 &= 225 + 12 - 4 \\
 &= 233 \text{ Elements}
 \end{aligned}$$

9 Piece Cd Slab Array and 9 Piece Boral Slab Array (slabs 2" wide)

0.5" Dia. Cd Rod 9 Piece Array

$$\begin{aligned}
 M_c &= (15 \times 15) + 4(4) - (9+4) \\
 &= 225 + 16 - 13 \\
 &= 228 \text{ Elements}
 \end{aligned}$$

**2" Wide Cd Slab, double
2" Wide Boral Slab, double**

$$\begin{aligned}
 M_c &= (15 \times 15) + 4(4) - 6 \\
 &= 225 + 16 - 6 \\
 &= 235 \text{ Elements}
 \end{aligned}$$

● = Fuel Elements Removed

Figure 6a. LATTICE CONFIGURATIONS, H₂O, 93.2% FUEL
Lattice Pitch: 2.032 cm

0.5" Dia. Cd Rod, double

$$\begin{aligned} Mc &= (15 \times 15) + 4(3) - (4 + 2) \\ &= 225 + 12 - 6 \\ &= 231 \text{ Elements} \end{aligned}$$

Cd Angle, double

Boral Angle, double

$$\begin{aligned} Mc &= (15 \times 15) + 4(4) - 6 \\ &= 225 + 16 - 6 \\ &= 235 \text{ Elements} \end{aligned}$$

2" Dia. Cd Annulus, double

$$\begin{aligned} Mc &= (17 \times 17) - (18 \text{ center} + 12 \\ &\quad \text{corner elements}) \\ &= 289 - 30 \\ &= 259 \text{ Elements} \end{aligned}$$

● = Fuel Elements Removed

Figure 6b. LATTICE CONFIGURATIONS, H₂O, 93.2% FUEL
Lattice Pitch: 2.032 cm

1" Dia. Rods: B_4C , Dy_2O_3 , $Dy_2O_3 - B_4C$,
and Cd Annulus, Empty and
Moderator Filled

$$\begin{aligned} M_c &= (15 \times 15) + 4(5) - 5 \\ &= 225 + 20 - 5 \\ &= 240 \text{ Elements} \end{aligned}$$

2" Dia. Cd Annulus

$$\begin{aligned} M_c &= (17 \times 17) - (9 \text{ center} + 24 \text{ corner elements}) \\ &= 289 - 33 \\ &= 256 \text{ Elements} \end{aligned}$$

Cd Angle
Boral Angle

$$\begin{aligned} M_c &= (15 \times 15) + 4(4) - 3 \\ &= 225 + 16 - 3 \\ &= 238 \text{ Elements} \end{aligned}$$

● = Fuel Elements Removed

Figure 6c. LATTICE CONFIGURATIONS, H_2O , 93.2% FUEL
Lattice pitch: 2.032 cm

0.5" Dia. Cd Rod Centrally Located: Core Same as Basic Core, Except
the Center Element is Removed

$$M_c = 233 - 1 = 232 \text{ Elements}$$

2" Cd Slab Centrally Located and
2" Boral Slab Centrally Located

$$\begin{aligned} M_c &= (15 \times 15) + 4(4) - 3 \\ &= 225 + 16 - 3 \\ &= 238 \text{ Elements} \end{aligned}$$

10" Wide Ag - Cd Slab and
10" Wide Cd Slab

$$\begin{aligned} M_c &= (15 \times 15) + 4(9) \\ &\quad - (4 \text{ corner} + 13 \text{ center elements}) \\ &= 225 + 36 - 17 \\ &= 244 \text{ Elements} \end{aligned}$$

● = Fuel Elements Removed

Figure 6d. LATTICE CONFIGURATIONS, H_2O , 93.2% FUEL
Lattice Pitch: 2.032 cm

$D_2O - A$

$D_2O - B$

● = Elements Removed

$D_2O - C$

$D_2O - D$

Note; Above configurations represent regional changes in basic cores described below.

Basic Cores:

1.3%: Rectangular parallelepiped with 20×20 square array of fuel elements.
Lattice Pitch: 4.064 cm

3.0%: Rectangular parallelepiped with 14×14 square array of fuel elements.
Lattice Pitch: 4.064 cm

Figure 7. LATTICE CONFIGURATIONS, D_2O , 1.3% AND 3.0% FUEL

Basic Core

$$M_c = (8 \times 10) + 4$$

$$= 84 \text{ Elements}$$

$H_c = 114.56 \text{ cm.}, 114.73 \text{ cm.},$
or 114.96 cm.

2" Dia. Cadmium Annulus

$$M_c = (8 \times 10) + 4$$

$$= 84 \text{ Elements}$$

2" Dia. Cadmium Annulus, double

$$M_c = (8 \times 10) + 4$$

$$= 84 \text{ Elements}$$

Figure 8a. LATTICE CONFIGURATIONS, D_2O , 93.2% FUEL
Lattice Pitch: 4.064 cm

Boral Angle
Cadmium Angle

Mc = Basic Core
= 84 Elements

2" Wide Cadmium Slab
2" Wide Boral Slab
0.5" Dia. Cadmium Rod

Mc = Basic Core
= 84 Elements

1" Dia. Rod Cases:
B₄C, Dy₂O₃- B₄C,
Dy₂O₃ & Cadmium
Annulus, Empty &
Moderator, Filled

Mc = Basic Core
= 84 Elements

Figure 8b. LATTICE CONFIGURATIONS, D₂O, 93.2% FUEL

10" Wide Cadmium Slab &
10" Wide Ag-Cd Slab

Mc = Basic Core
= 84 Elements

2" Wide Cadmium Slab, double
2" Wide Boral Slab, double
0.5" Dia. Cadmium Rod, double

Mc = Basic Core
= 84 Elements

Cadmium Angle, double
Boral Angle, double

Mc = Basic Core
= 84 Elements

Figure 8c. LATTICE CONFIGURATIONS, D_2O , 93.2% FUEL

9 - Piece 2" Wide Cadmium Slab Array &
9 - Piece 2" Wide Boron Slab Array

Mc = Basic Core
= 84 Elements

9 - Piece 0.5" Dia. Cadmium Rod Array

Mc = Basic Core
= 84 Elements

Control Rods

○ Fuel

Figure 8d. LATTICE CONFIGURATIONS, D₂O, 93.2% FUEL

Test Section Enrichment	Number of Fuel Elements in Driver Region	
	1.3%	1.6%
1.3%	1608	272
3.0%	1600	169
93.2%	1292, (1268)*	

* With graphite filler plugs in core.

Basic Core:

Graphite test section (same for all 3 enrichments),
60.96 cm in diameter containing 94 fuel elements
and graphite filler plugs, the latter placed into
the two experimental holes of 2" dia., approximately
4" north and south of the center slot, (0.5"x10").

Lattice Pitch: 5.080 cm

Peripheral Driver Region Configurations:

Lattice Pitch: 2.032 cm

Figure 9. LATTICE CONFIGURATIONS, GRAPHITE, 1.3%, 3.0%, AND 93.2% FUEL

Basic Core:

1.3% : Rectangular parallelepiped with a 43×43 square array of fuel elements minus the four corner elements.
 $M_c = 43 \times 43 - 4 = 1845$ elements.
 Lattice Pitch: 2.032 cm

3% : $M_c = 729$ elements
 Lattice Pitch : 2.032 cm

Note: Lattice modifications to accommodate control rods are equivalent to those of the H_2O , 1.3% core, Figure 4, except for H_2O -K, where only 9 elements were removed.

Figure 10. LATTICE CONFIGURATION, ORGANIC, 1.3% & 3% FUEL

General: Rod consists of solid aluminum end plug (A), active cadmium region (B) of 0.380" diameter, clad in aluminum tube 0.5" O.D. with 0.049" wall. Top end (C) of aluminum cladding is a threaded solid aluminum plug.

Short Rod		
A	B	C
0.5"	48"	13.5"

Long Rod		
A	B	C
2.5"	73"	9"

Figure 11. 0.5" DIAMETER CADMIUM ROD

Short Slab	
A	B
0.375"	59.75"

Long Slab	
A	B
2.50"	80.25"

Figure 12. 2" WIDE (NOMINAL) CADMIUM SLAB

Short Angle	
A	B
0.375"	59.75"

Long Angle	
A	B
2.75"	80"

Figure 13. CADMIUM ANGLE

Short Angle	
A	B
0.375"	59.75"

Long Angle	
A	B
2.50"	80.25"

Figure 14. BORAL ANGLE

Short Tube	
A	B
0.375"	59.75"

Long Tube	
A	B
2.50"	80.25"

Figure 15. 2" DIAMETER (NOMINAL) CADMIUM ANNULUS

Short Rod	
A	B
0.188"	48"

Long Rod	
A	B
2.25"	72"

Figure 16. 1" DIAMETER B₄C AND Dy₂O₃ RODS

Figure 17. 1" DIAMETER B_4C - Dy_2O_3 ROD

Figure 18. 1" DIAMETER CADMIUM ANNULUS

Section X - X

Figure 19. 10" WIDE B_2O_3 SLAB

Short Slab	
A	B
0.375"	59.75"

Long Slab	
A	B
2.50"	80.25"

Figure 20. 2" WIDE (NOMINAL) BORAL SLAB

TYPICAL 10" SLAB

Short Slab

A	B
0.375"	48"

Long Slab

A	B
2.5"	73"

Figure 21a. CADMIUM SLAB

Short Slab

A	B
0.375"	48"

Long Slab

A	B
2.5"	73"

Figure 21b. SILVER - CADMIUM SLAB

Target

High Voltage

Figure 22. PULSED NEUTRON SOURCE, ACCELERATOR TUBE

Figure 23. EXPERIMENTAL APPARATUS AND DATA ANALYSIS SYSTEMS

Figure 24. COUNT RATE VERSUS TIME AFTER PULSING A SUBCRITICAL REACTOR

Figure 25. VERTICAL FLUX TRAVERSE, H_2O , 93.2% FUEL

Figure 26. HORIZONTAL FLUX TRAVERSE, H_2O , 93.2% FUEL

Figure 27. VERTICAL FLUX TRAVERSE, D₂O, 1.3% FUEL

Figure 28. HORIZONTAL FLUX TRAVERSE, D_2O , 1.3% FUEL

Figure 29. VERTICAL FLUX TRAVERSE, D₂O, 3% FUEL

Figure 30. HORIZONTAL FLUX TRAVERSE, D₂O, 3% FUEL

Figure 31. VERTICAL FLUX TRAVERSE, D_2O , 93.2% FUEL

Figure 32. HORIZONTAL FLUX TRAVERSE D₂O 93.2% FUEL (NORTH - SOUTH)

Figure 33. HORIZONTAL FLUX TRAVERSE, D_2O , 93.2% FUEL (EAST - WEST)

Figure 34. VERTICAL FLUX TRAVERSE IN GRAPHITE (2 INCHES OFF CENTER LINE), 1.3% FUEL

Figure 35. HORIZONTAL FLUX TRAVERSE, GRAPHITE, 1.3% FUEL

Figure 36. VERTICAL FLUX TRAVERSE IN GRAPHITE (2 INCHES OFF CENTER LINE), 3% FUEL

Figure 37. HORIZONTAL FLUX TRAVERSE, GRAPHITE, 3% FUEL

Figure 38. VERTICAL FLUX TRAVERSE IN GRAPHITE (2 INCHES OFF CENTER LINE), 93.2%-FUEL

Figure 39. HORIZONTAL FLUX TRAVERSE, GRAPHITE, 93.2% FUEL

Figure 40. VERTICAL FLUX TRAVERSE, ORGANIC, 1.3% FUEL

Figure 41. HORIZONTAL FLUX TRAVERSE, ORGANIC, 1.3% FUEL

Figure 42. VERTICAL FLUX TRAVERSE, ORGANIC, 3% FUEL

Figure 43. HORIZONTAL FLUX TRAVERSE IN ORGANIC, 3% FUEL

Figure 44. PULSED NEUTRON SOURCE AND DETECTOR LOCATIONS

Figure 45. ALPHA VERSUS BUCKLING FOR LIGHT WATER

Figure 46. ALPHA VERSUS BUCKLING FOR LIGHT WATER

Figure 47. ALPHA VERSUS BUCKLING FOR HEAVY WATER

Figure 48. ALPHA VERSUS BUCKLING FOR GRAPHITE

Figure 49. ALPHA VERSUS BUCKLING FOR ORGANIC

Figure 50. PROMPT DECAY CONSTANTS, H₂O, 1.3% FUEL

Figure 51. PROMPT DECAY CONSTANTS, H₂ O, 3% FUEL

Figure 52. PROMPT DECAY CONSTANTS, H₂O, 93.2% FUEL

Figure 53. PROMPT DECAY CONSTANTS, D₂O, 1.3% FUEL

Figure 54. PROMPT DECAY CONSTANTS, D₂O, 3% FUEL

Figure 55. PROMPT DECAY CONSTANTS, D₂O, 93.2% FUEL

Figure 56. PROMPT DECAY CONSTANTS, GRAPHITE, 1.3% FUEL

Figure 57. PROMPT DECAY CONSTANTS, GRAPHITE, 3% FUEL

Figure 58. PROMPT DECAY CONSTANTS, GRAPHITE, 93.2% FUEL

Figure 59. PROMPT DECAY CONSTANTS, ORGANIC, 1.3% FUEL

Figure 60. PROMPT DECAY CONSTANTS, ORGANIC, 3% FUEL

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It is with deep regret that we inform the readers of W. C. Ballowe's death on March 14, 1962. He died of injuries suffered in an automobile accident on March 8 near the laboratory.