GENERAL ATOMIC

DIVISION OF **GENERAL DYNAMICS**

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MEASUREMENTS OF SUBCRITICAL REACTIVITY USING A PULSED-NEUTRON SOURCE

Contract AT(04-3)-167
Project Agreement No. 2
U. S. Atomic Energy Commission

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I. INTRODUCTION

Pulsed neutron source measurements have been made for a series of subcritical to cricital loadings on a bare U-235 water assembly in slab geometry. The measurements cover the range from 30 $ subcritical to a measurement at critical. The purpose of the measurements has been to investigate methods for determining subcritical reactivities by the pulsed neutron source method in a clean geometry. For each loading investigated, the assembly is repetitively pulsed and the complete time distribution of thermal neutrons in the core is recorded on time analyzers. From these data a determination of α, the delayed neutron background and the reactivity of the system is determined. Measurements at various positions in the assembly have been performed to verify that spatial modes do not affect the reactivity determination.

The General Atomic Linear Accelerator (electron) was used for the pulsed neutron source. A heavy metal target of tungsten Fansteel just outside one face of the assembly was used to convert the electrons to neutrons. Approximately 10^7 neutrons per pulse were used with typical accelerator conditions of 30 Mev, o.1 microsecond pulse width, pulse repetition rates from 30 to 120 pps and an electron current of from 1 to 5 milliamps per pulse.

II. CORE ASSEMBLY

The U-235 water assembly has previously been used at the linear accelerator facility for measurement of neutron spectra[1] by time-of-flight techniques at a multiplication of approximately 10.

The assembly is of slab geometry with 20 mil uranium-aluminum fuel plates spaced with 1/8" water gaps. The transverse dimensions of the fuel plates and the water tank are 18" by 18". The core thickness at critical was 8.64 inches. Each 18 x 18 x 0.020 inch fuel plate contains 51.4 grams of U-235. The assembly is bare, being cadmium lined on the sides and bottom and having a borated glass cover on the top. The assembly was set up in a large room far from walls and ceiling in order to reduce time-dependent effects from room return. The nearest room boundary was the floor 8 ft away with the walls and ceiling being at least 15 ft away. Figure 1 shows the details of the core and tank and Fig. 2 shows a photograph of the assembly looking towards the electron beam tube. Two blade type cadmium control rods are used and replace part of one fuel plate. A one-half inch diameter tube, or "glory hole", extends through the center of the thin dimension of the assembly. In this tube a small fission counter can be remotely positioned at any desired point in the thin dimension.

As the loading of fuel progresses, the boundary is also moved. This movable boundary is a cadmium covered aluminum plate to simulate the fixed side of the tank. Beyond this boundary, water is excluded by the use of hollow aluminum rectangular tanks to void the region.

The movable boundary is clamped in position after each loading change. The spacing between fuel plates is established by polyethylene spacer ribs attached to the fuel plates. A plutonium-beryllium source (5 curies) is used for start up and multiplication measurements and can be retracted into a shielded container during pulsed source experiments.

III. PULSING THE ASSEMBLY

To obtain data on the time behavior of the neutrons after a pulse, the assembly is repetitively pulsed at repetition rates in the range from 30 to 120 pps, depending upon the die away time. The counts from the small fission counter in the glory hole are time analyzed using multichannel analyzers. Two analyzers have been used simultaneously, both being triggered on at 4 microseconds after the pulse source. A 1024 channel TMC analyzer is used to obtain the detailed shape of the time distribution, being set typically on 2 to 20 microsecond channel widths. A 256 channel RCL analyzer with typically 16, 32 or 64 microsecond channel widths is used as a check.

By relatively rapid pulsing, the delayed neutron population reaches equilibrium, decays negligibly during the time between pulses, and is treated as a constant background. In obtaining the entire time behavior from just after one pulse to just before the next, data similar to that shown in Fig. 3 are obtained. The next pulse occurs at 16.7 milliseconds on Fig. 3. This typical pulse consists of three main parts. First, at early times, there is a transient region during which spatial modal effects are apparent. Second, there is the time region over which the neutrons die away exponentially with the fundamental spatial mode (in this assembly a cosine) characteristic. Third, at long times the delayed neutrons are seen as a slowly decaying background.

IV. SPATIAL MODES

Determination of the die-away of the fundamental mode is necessary to obtain the value of α for the assembly loading. To determine the effects of higher harmonics at early times, a spatial modal analysis was made for three of the loadings. This was done by obtaining the time behavior of the neutron population at each of as many as 12 space points across the thin core dimension. At each time point the spatial distribution was then harmonically analyzed for up to six modes. Fig. 4 shows the type of spatial distribution encountered at various times after a repetitive pulse. The pulsed source is 3 inches to the left of the core face in this figure. It is seen that the distribution is initially peaked toward the source side, and rather rapidly redistributes to a cosine distribution. Figure 5 shows the results of the harmonic analysis for this case, in which two higher harmonics were included. In this case as in the other two loadings for which the modal analysis was carried out, the higher harmonics die out in a short time and leave only the fundamental decay. In all cases with this assembly the contribution of the higher harmonics was negligible after about 200-300 microseconds. The curvature of the fundamental mode at early times is due to modes in the transverse dimensions which were not included in this analysis. The fitting of an exponential was made to data after this time to eliminate any contribution from higher harmonics. A flux plot taken at critical with uranium-aluminum foils is shown in Fig. 6, giving a good fit to a cosine distribution. This gives a thermal extrapolation length of 0.88" (2.24 cm).

V. DETERMINATION OF α

The determination of the reciprocal of the die-away time, which is commonly called α, is accomplished by fitting an exponential to the data over the appropriate region. First the data are corrected for count loss, if any, by a code in Fortran for the IBM 7090. The count loss corrections are kept below 5 to 10% by adjusting the count rate (adjusting the intensity of the pulsed source). Second, the constant delayed neutron background is determined by averaging over many time channels, and this is subtracted from the count loss corrected data. Third, a least squares weighted fit to an exponential of the form $e^{-\alpha t}$ is made by a machine code over the time region of the fundamental mode decay. This fit is weighted by the inverse square of the relative standard deviation of the counts in each time channel. This gives a value for α with a statistal uncertainty of a fraction of a percent. The α determined from the two time analyzers agreed to better than one-half of one percent.

The determination of α at delayed critical was accomplished by pulsing at critical and also by extrapolating several measurements of α near critical to critical. The two results agreed within one percent and the value used is the measured value at critical. At critical, pulsing presents several problems in the determination of α. First, each pulse raises the power a small amount and after a number of pulses, the assembly power must be reduced with the control rods and criticality established again at lower power. In these experiments, sufficient data were obtained in one power rise from a small fraction of a watt to approximately 50 watts. Additional power rises could have been used to accumulate more statistics. The second problem is associated with the delayed neutron background at critical. Since it is a large part of the observed count, the subtraction leads to a small number of counts per channel for determining the α_c. In these experiments, sufficient counts were obtained to determine the α_c to a little better than one percent.

VI. DETERMINATION OF REACTIVITY

In determining the subcritical reactivity from the pulsed source measurements, the commonly used expression: $\$ = \frac{\alpha}{\alpha_c} - 1$ was used as well as the recent Garelis and Russell[2] method which is sometimes referred to as the $(k\,\beta/\ell)$ method. This latter method does not require knowledge of the critical α.

The relationship between these two methods can be seen as follows. Using the definition of α and reactivity in \$ as follows:

$$\alpha = \frac{1-k(1-\beta)}{\ell} \text{ and } \$ = \frac{1-k}{\beta}$$

where: k is the multiplication constant, ℓ is the prompt neutron lifetime and β is the effective delayed neutron fraction. Then:

$$\alpha = \beta/\ell\,(\$ + k) \text{ or } \$ = \frac{\alpha}{\beta/\ell} - k$$

If k is near unity and β/ℓ is assumed constant we get the familiar expression:

$$\$ = \frac{\alpha}{\alpha_c} - 1$$

In the Garelis and Russell method, the value of $(k\beta/\ell)$ is determined from the experimental data as follows:

$$\frac{N_D}{R} = \int_0^{1/R} N_p \left(e^{\frac{k\beta}{\ell} t} - 1\right) dt$$

where: N_D is the constant delayed neutron background

R is the pulse repetition rate

N_P is the experimental data with the N_D subtracted

In this expression, everything is known except $(k\beta/\ell)$ so the procedure is to iterate for this quantity. The integral is in practice taken to infinity since essentially no prompt neutrons exist after several decades of exponential fall off. For \$ defined in the same form as in the in-hour equation, namely:

$$\$ = \frac{1-k}{k\beta}$$

then we have in the Garelis-Russell method:

$$\$ = \frac{\alpha}{k\beta/\ell} - 1$$

If no modal effects exist at early times, that is if the exponential decay of the fundamental mode extends from time zero (a condition which was met experimentally in some of these measurements by proper placement of the detector) then a simplified expression results from the Garelis-Russell method:

$$\$ = \frac{RQ}{N_D \cdot \alpha}$$

where Q is the value of N_p at t=0, i.e. $N_p = Qe^{-\alpha t}$

Table I gives the results for the α determination for the various subcritical cases and the reactivity resulting.

Figure 7 shows a plot of the comparison of α vs \$ for the two methods of determining \$. The two methods converge near critical.

Figure 8 shows a plot of the $k\beta/\ell$ determined by the Garelis-Russell method vs the \$ subcritical. A 20% decrease in $k\beta/\ell$ is observed over a reactivity change of about 20%. This change is attributed to the leakage change since no change in $k\beta/\ell$ would be expected if the reactivity were changed by adding a

1/v absorber to the critical size assembly. This latter point has not been checked in these experiments. Calculations are proceeding to calculate the change in $k\beta/\ell$ for the assembly and preliminary results give a change in the same direction but of about half the magnitude. Further calculations may help explain this.

The Garelis-Russell method of determining reactivity is, in the formulation of Ref. 2, independent of spatial modal effects. To experimentally verify this point, measurements were made on two loadings for the counter in several positions in the core. Every point in the core has the same α and should lead to the same result for reactivity. Measurements were made with the fission counter in three positions, on the boundary of the core nearest the pulsed source, at the core center, and on the boundary furthest from the pulsed source. The shape of the neutron vs time vehavior at early times is shown for one core loading in Fig. 9. These shapes are drastically different due to different effects of spatial modes and yet the reactivity determined at each of these three positions using the analysis of the Garelis and Russell method was within $\pm$ 1%. The results can be seen in Table I at loadings 8 and 11. Figure 9 also indicates that there is a position between 0 and 4 inches where modal effects are minimized.

TABLE I

Loading Number	Grams U-235	Core Thickness Inches	Pulses Per Sec.	Counter Inches From Source Side	α Sec	Garelis-Russell $	Garelis-Russell $k\beta/\ell$	αc $
19 (Critical)	2921.51	8.64	30	0	231.7	0	231.7	0
18	2904.47	8.50	30	0	285.1	0.239	230	0.23
15	2852.95	8.38	30	Center	560.0	1.41	232	1.42
12	2801.66	8.14	60	Center	759.1	2.37	225	2.28
11	2750.17	8.04	60	0	1221.7	4.50	222	4.27
			60	4	1235.3	4.51	222	4.33
			60	8	1250.8	4.56	225	4.40
10	2647.45	7.72	60	Center	1759.2	6.94	221	6.59
9	2544.55	7.43	60	Center	2206.0	9.11	218	8.52
8	2390.55	6.99	60	0.5	3104	13.36	216	12.40
			60	3.0	3082	13.68	210	12.30
			60	6.5	3102	13.54	213	12.39
7	2236.40	6.53	60	3.25	4232.4	20.81	194	17.27
6	2082.26	6.10	60	3.25	5234.5	26.26	192	21.59
5	1928.05	5.63	120	2	6616.7	33.08	194	27.56
				3.25	6527.8	34.61	183	27.17

VII. OTHER MEASUREMENTS

Certain other measurements have been made in conjunction with this program and will be reported in a more complete report. These other measurements include the steady state source multiplication for all loadings and the reactivity determination for cases in which one control rod or both control rods are inserted into the core.

VIII. RESULTS

In general it appears that the use of pulsed neutron source techniques in subcritical assemblies can lead to useful data for nuclear analysis. In particular, the use of the analysis method of Garelis and Russell can provide information about subcritical reactivity without the need for taking the assembly to delayed critical. The application of the method to reflected systems has not been verified but appears to work (see Ref. 2). Further work in this direction is indicated.

REFERENCES

1. Young, J. C., et al. "Development of Multiplying Assembly." Final Report. G. A. Report GA-2471 (1961). Young, J. C. et al. "Measurements of Neutron Spectra and Decay Constants in a Water Moderated Multiplying Assembly." GA 2656 (1961).

2. E. Garelis, J. L. Russell, "Theory of Pulsed Neutron Source Measurements," NS and E 16, 263, (1963).

ASSEMBLY ARRANGEMENT AND DETAIL FUEL ARRANGEMENT

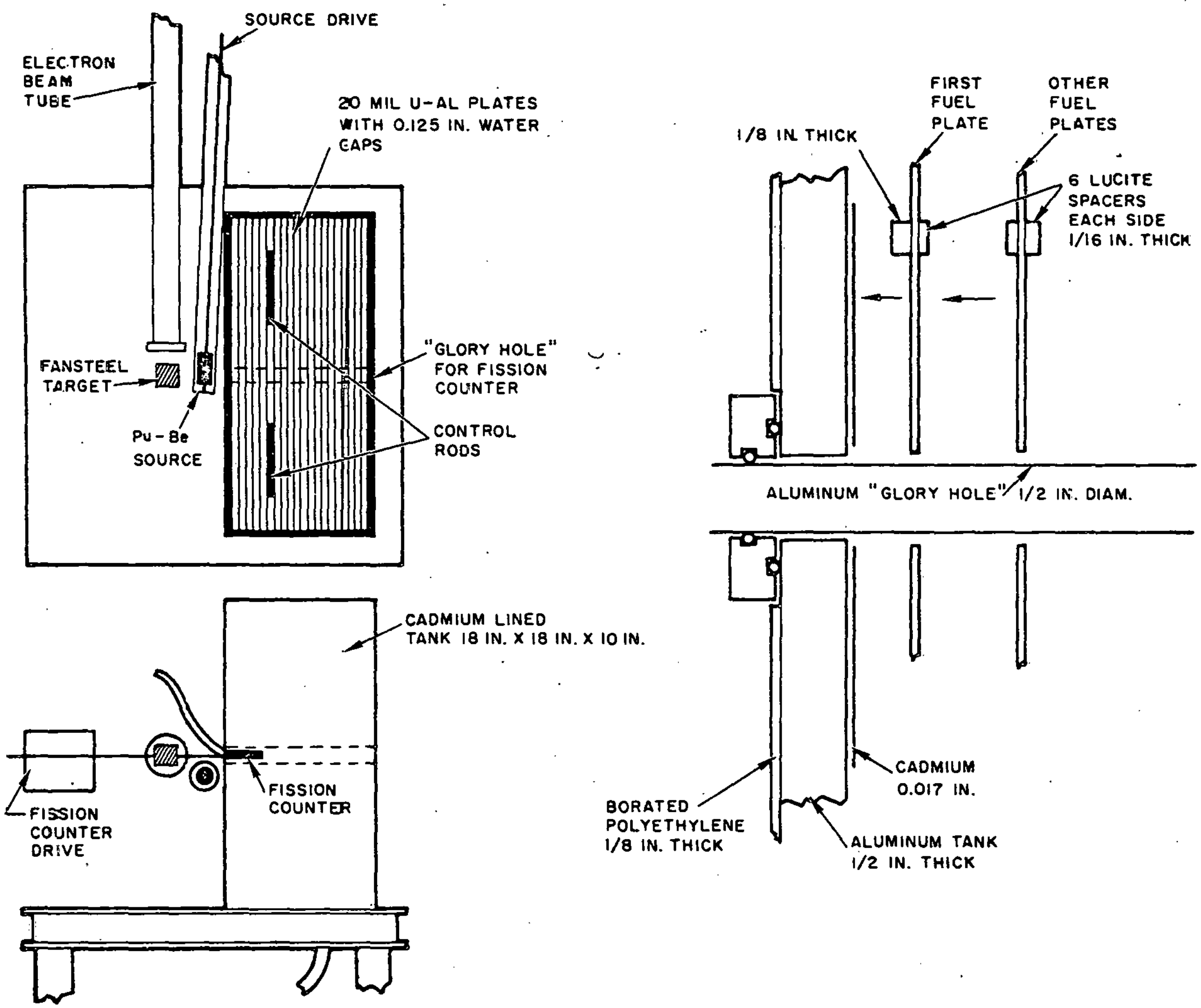


Fig. 1

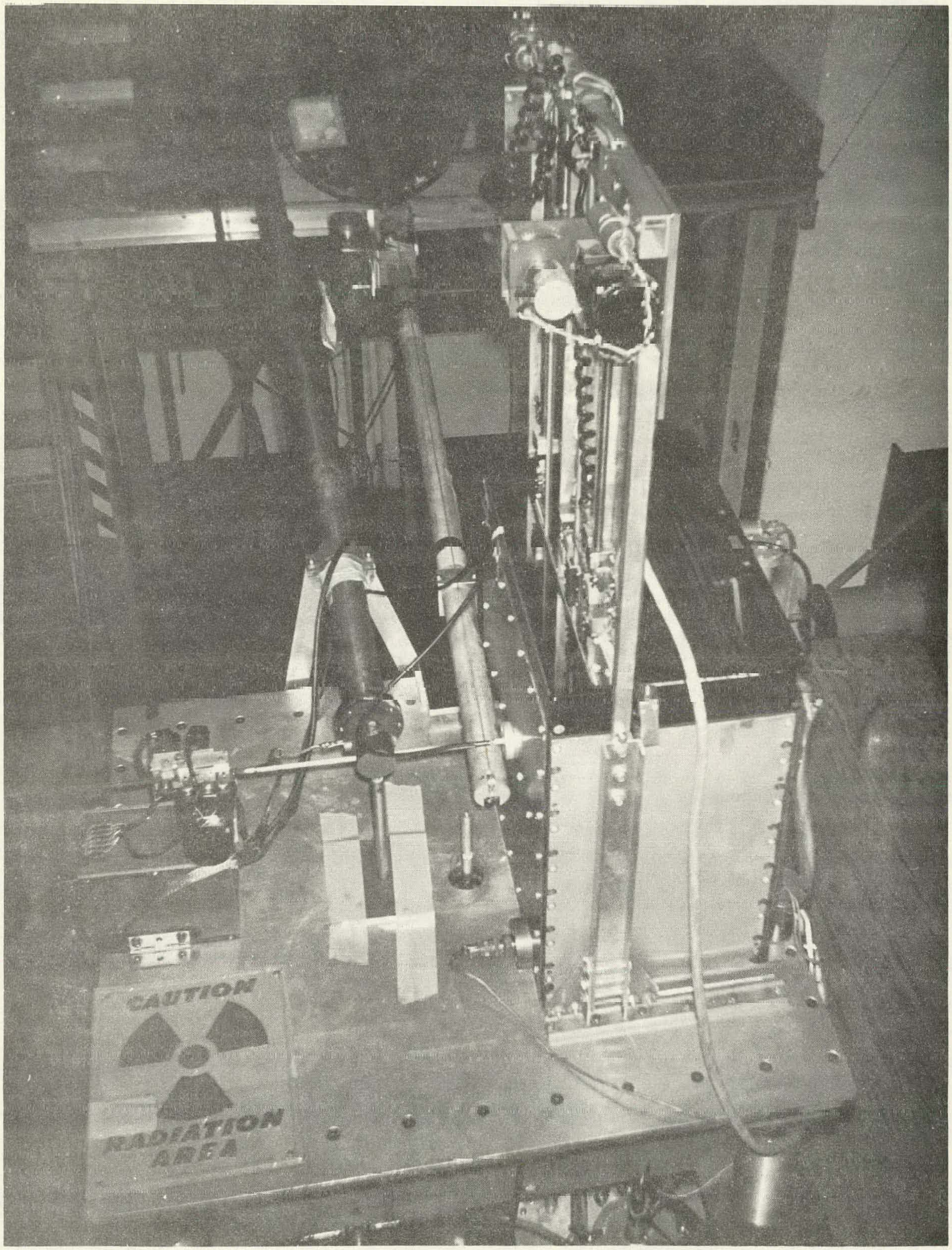
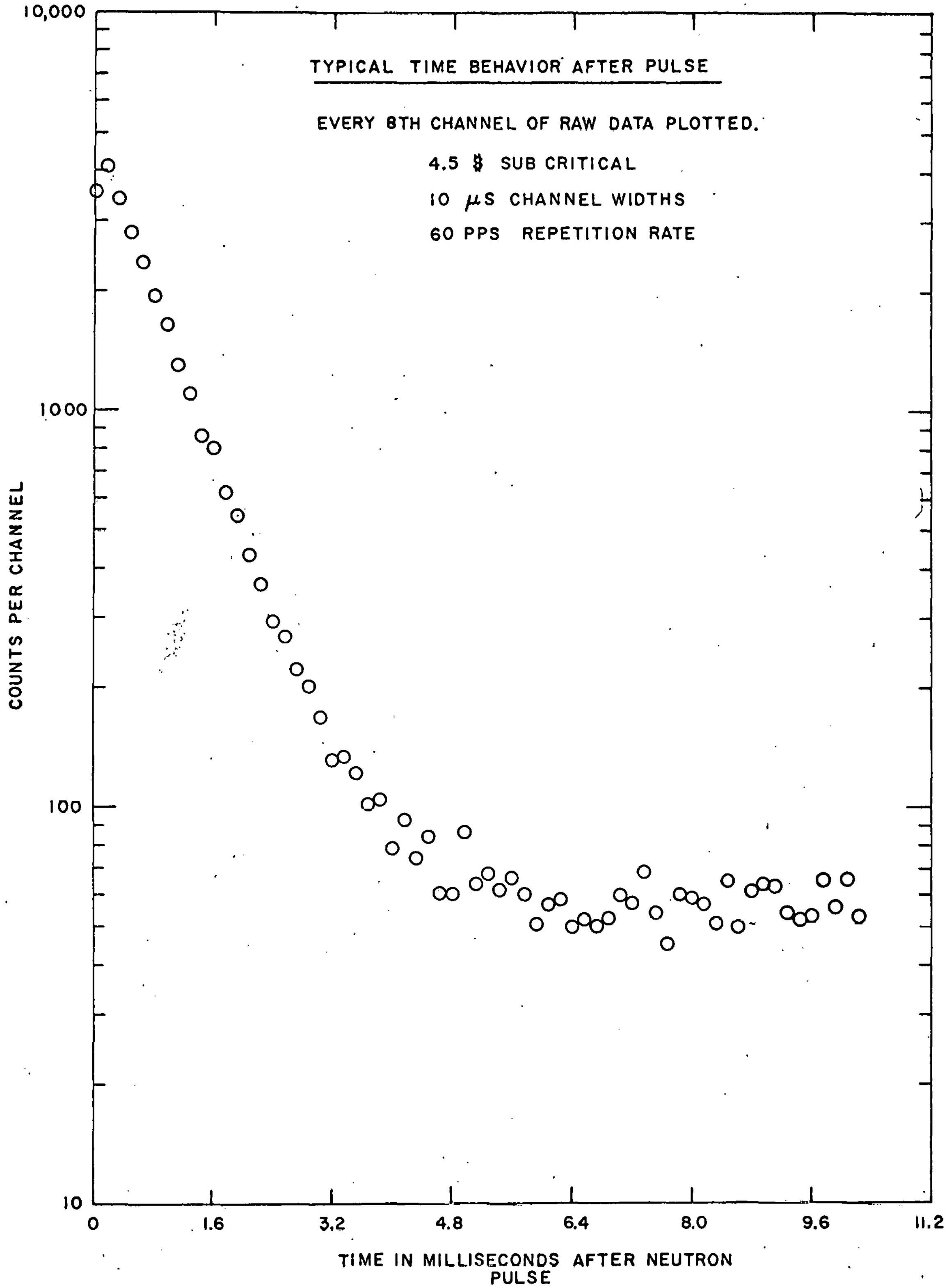


Fig. 2



TYPICAL TIME BEHAVIOR AFTER PULSE
EVERY 8TH CHANNEL OF RAW DATA PLOTTED.
4.5 $ SUB CRITICAL
10 μS CHANNEL WIDTHS
60 PPS REPETITION RATE
COUNTS PER CHANNEL
10,000
1000
100
10
0
1.6
3.2
4.8
6.4
8.0
9.6
11.2
TIME IN MILLISECONDS AFTER NEUTRON PULSE

Fig. 3

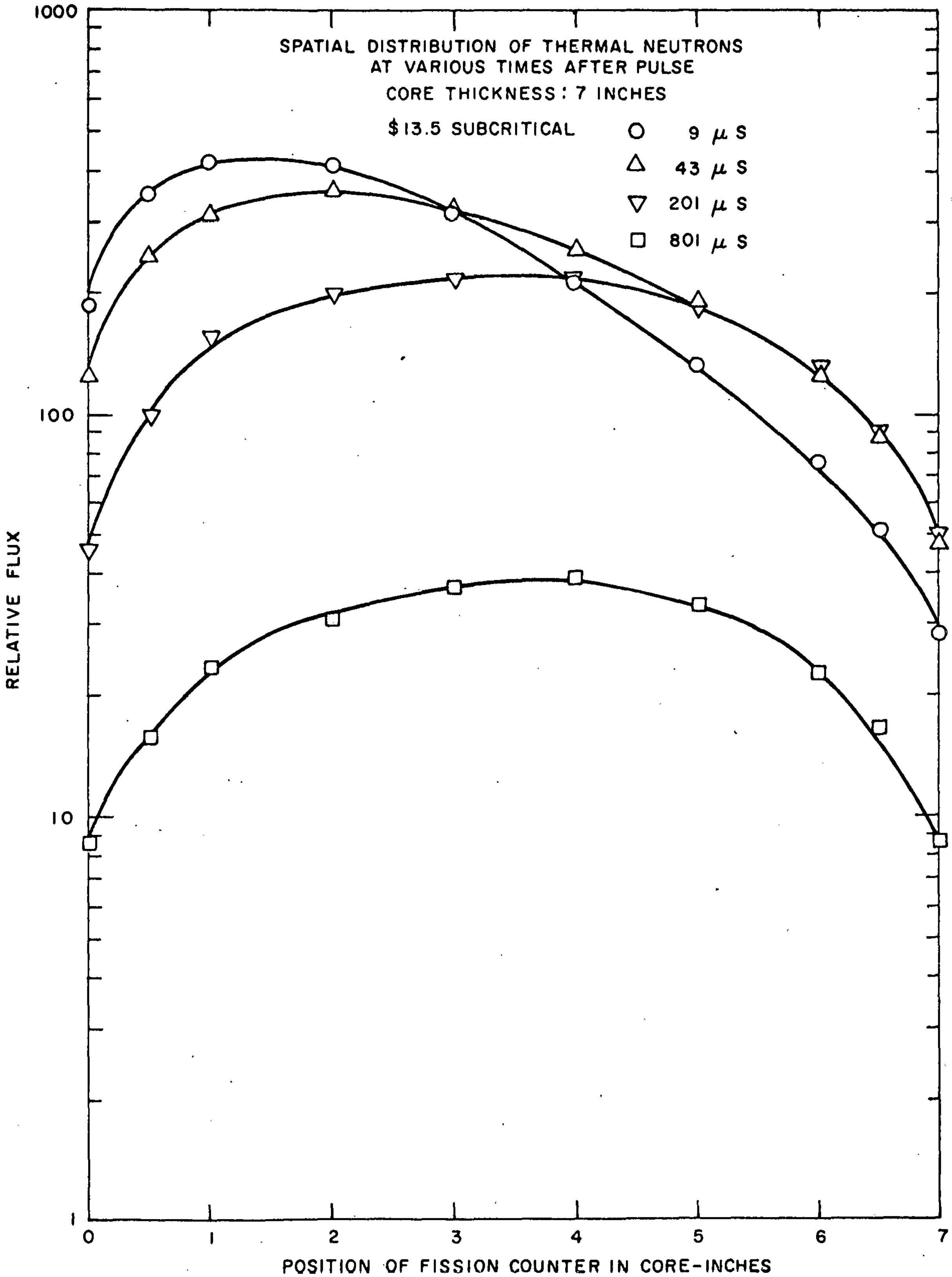

SPATIAL DISTRIBUTION OF THERMAL NEUTRONS
AT VARIOUS TIMES AFTER PULSE
CORE THICKNESS: 7 INCHES
$13.5 SUBCRITICAL
9 μ S
43 μ S
201 μ S
801 μ S
1000
100
10
1
0
1
2
3
4
5
6
7
RELATIVE FLUX
POSITION OF FISSION COUNTER IN CORE-INCHES

Fig.4

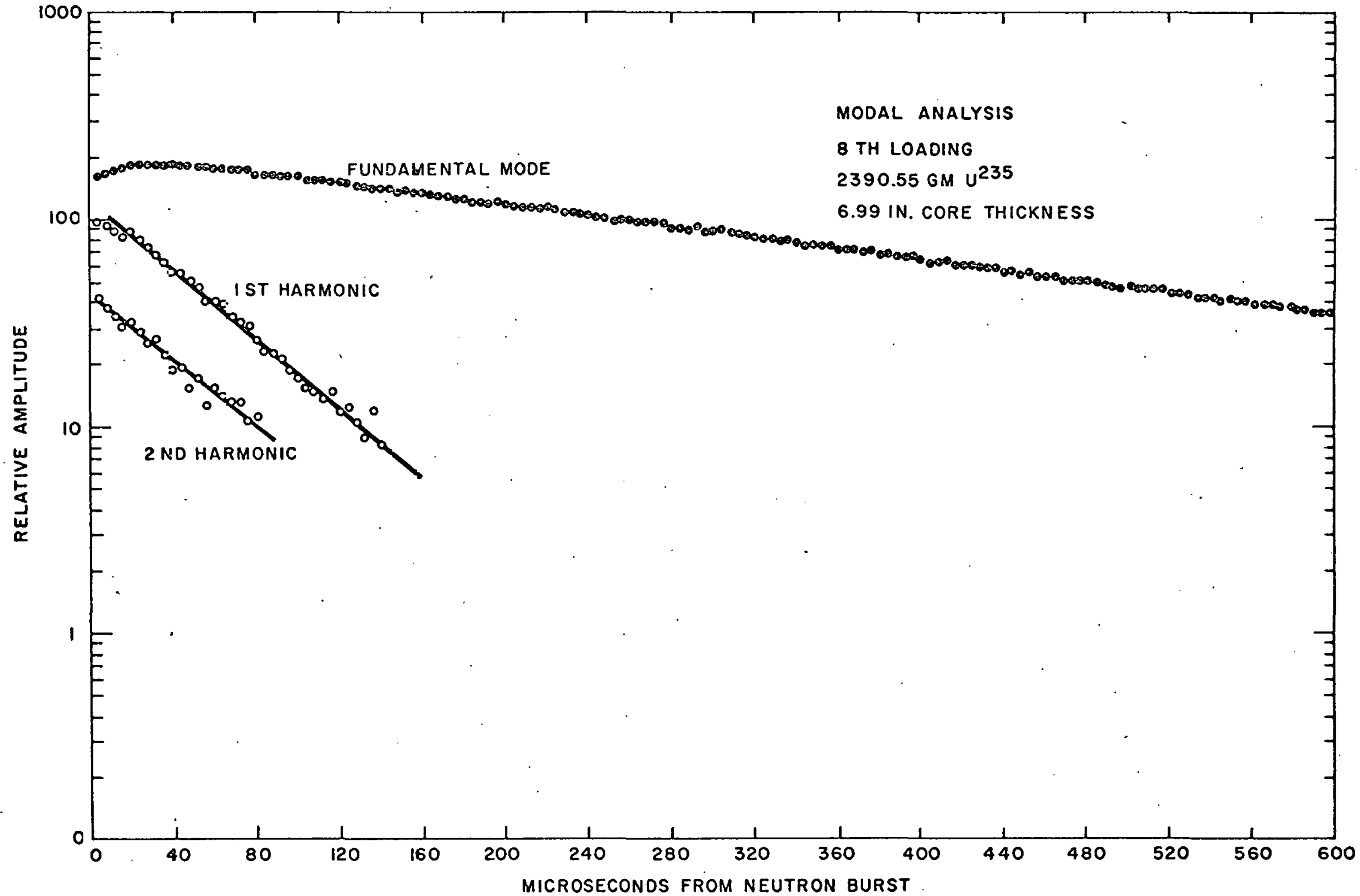

MODAL ANALYSIS
8 TH LOADING
2390.55 GM U^{235}
6.99 IN. CORE THICKNESS
FUNDAMENTAL MODE
1 ST HARMONIC
2 ND HARMONIC
RELATIVE AMPLITUDE
1000
100
10
1
0
0
40
80
120
160
200
240
280
320
360
400
440
480
520
560
600
MICROSECONDS FROM NEUTRON BURST

Fig. 5

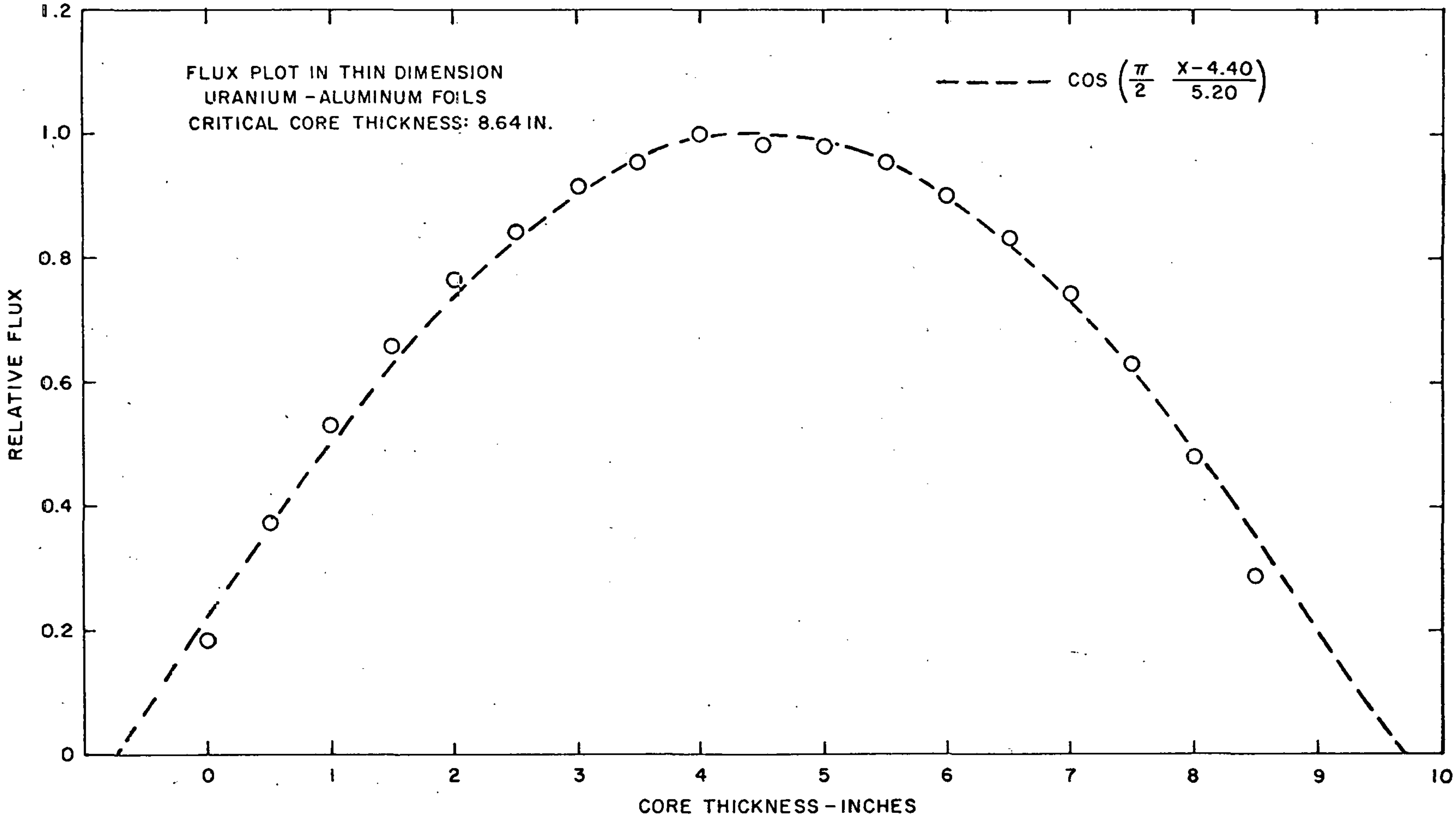

FLUX PLOT IN THIN DIMENSION
URANIUM-ALUMINUM FOILS
CRITICAL CORE THICKNESS: 8.64 IN.
$\cos\left(\frac{\pi}{2}\ \frac{X-4.40}{5.20}\right)$
RELATIVE FLUX
CORE THICKNESS - INCHES
0
0.2
0.4
0.6
0.8
1.0
1.2
0
1
2
3
4
5
6
7
8
9
10

Fig. 6

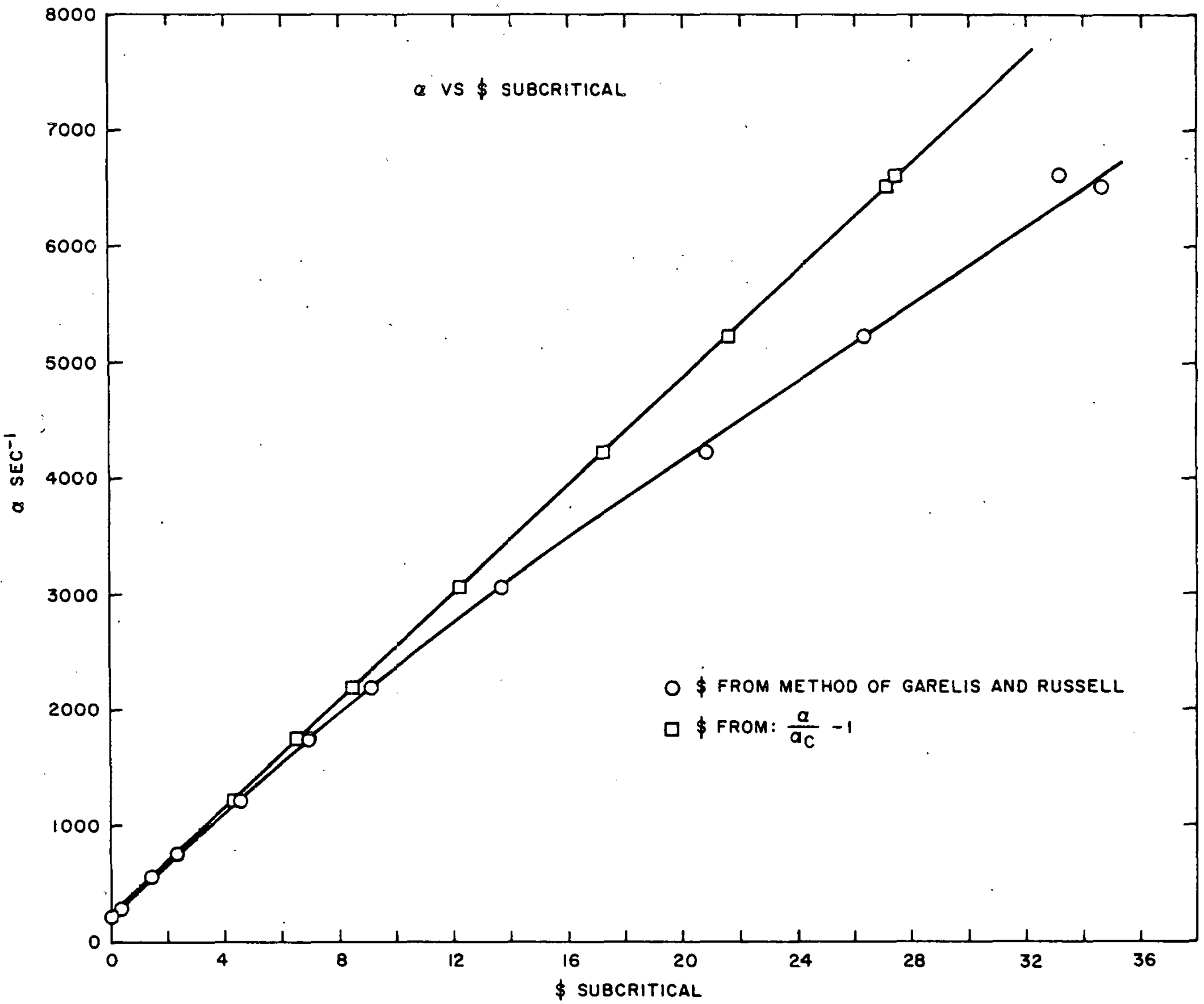

α VS $ SUBCRITICAL
α SEC⁻¹
$ SUBCRITICAL
$ FROM METHOD OF GARELIS AND RUSSELL
$ FROM: $\frac{\alpha}{\alpha_c} - 1$
0
1000
2000
3000
4000
5000
6000
7000
8000
0
4
8
12
16
20
24
28
32
36

Fig. 7

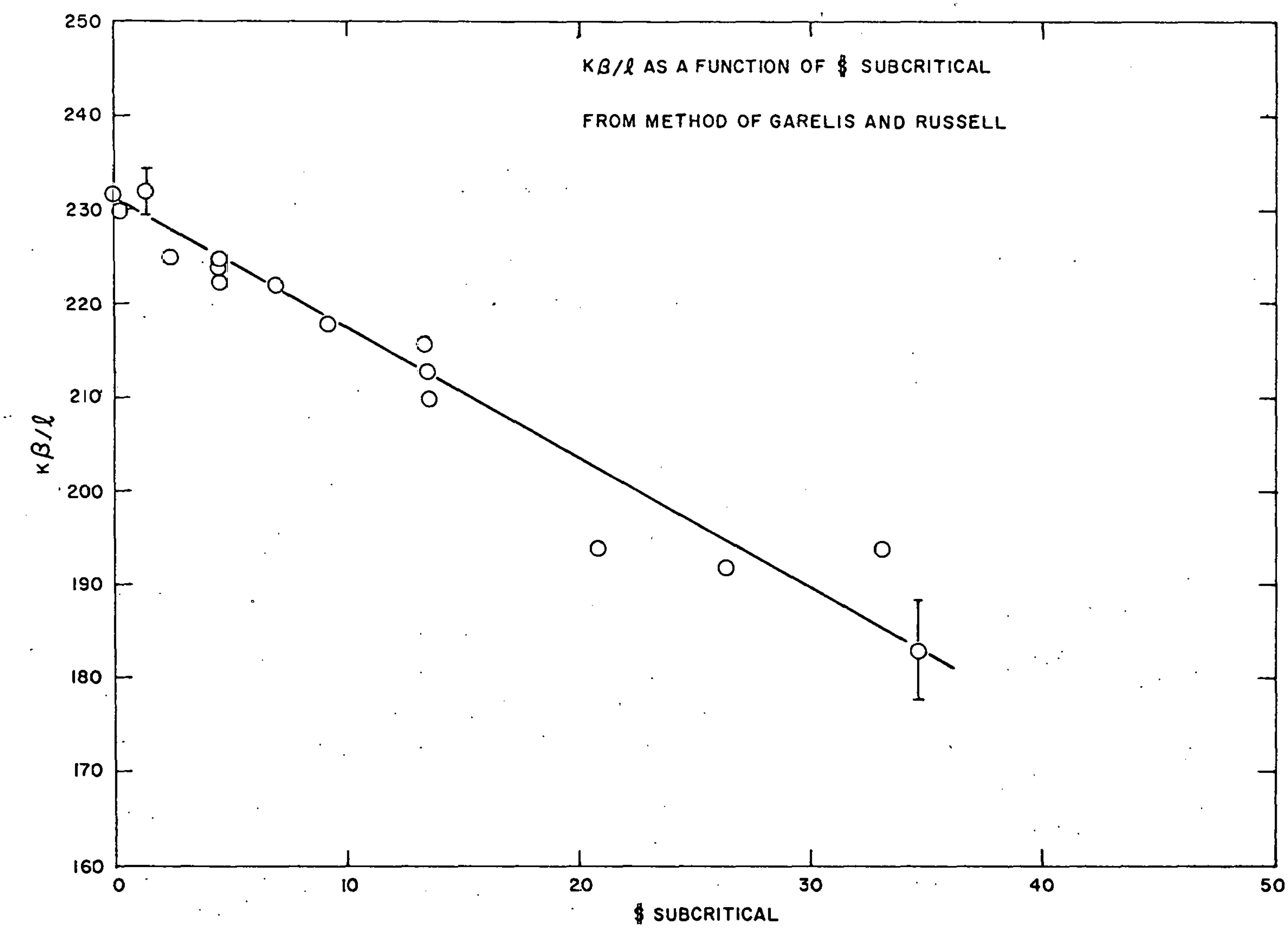

Kβ/ℓ AS A FUNCTION OF $ SUBCRITICAL
FROM METHOD OF GARELIS AND RUSSELL
Kβ/ℓ
250
240
230
220
210
200
190
180
170
160
0
10
20
30
40
50
$ SUBCRITICAL

Fig. 8

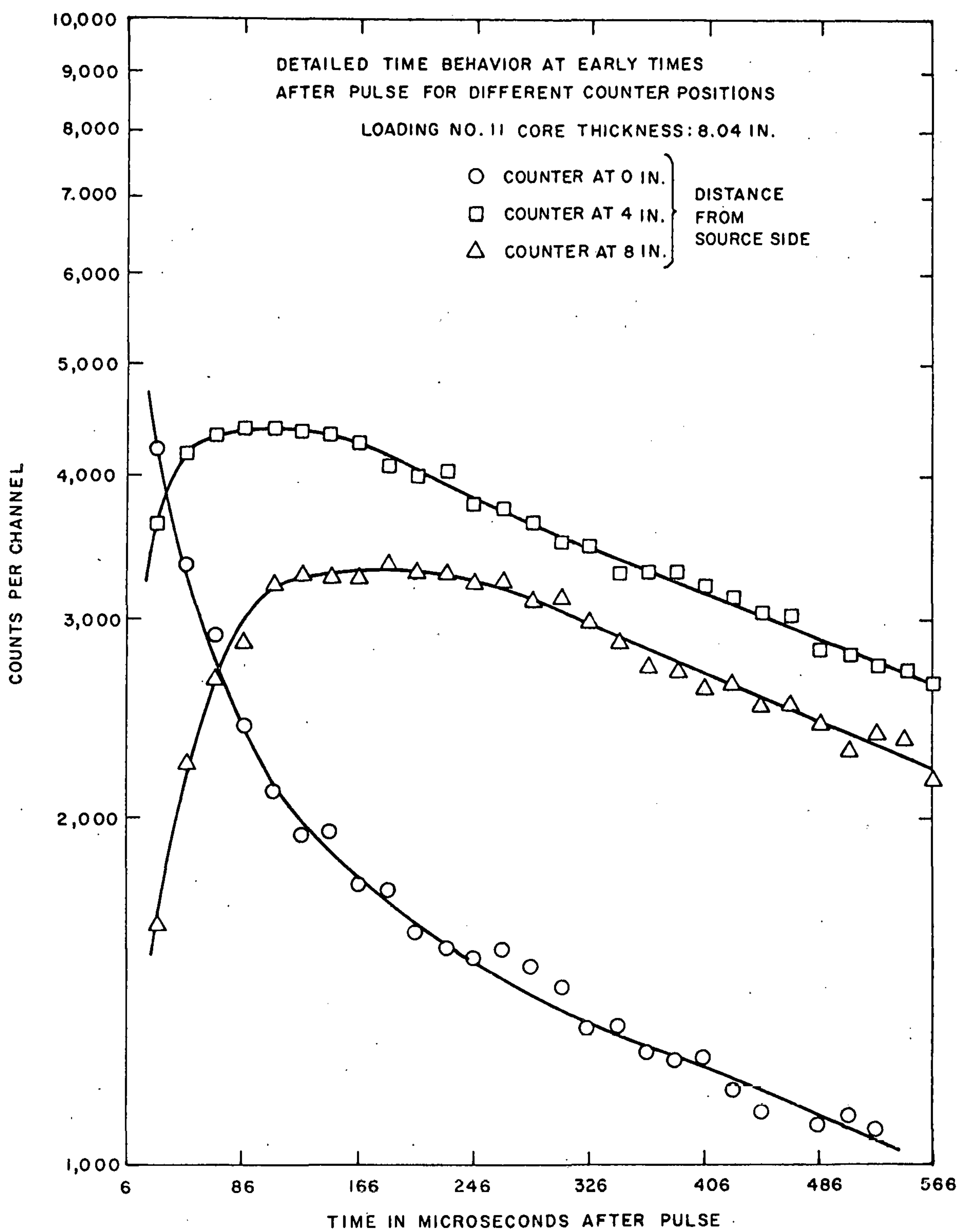

DETAILED TIME BEHAVIOR AT EARLY TIMES
AFTER PULSE FOR DIFFERENT COUNTER POSITIONS
LOADING NO. 11 CORE THICKNESS: 8.04 IN.
COUNTER AT 0 IN.
COUNTER AT 4 IN.
COUNTER AT 8 IN.
DISTANCE FROM SOURCE SIDE
COUNTS PER CHANNEL
10,000
9,000
8,000
7.000
6,000
5,000
4,000
3,000
2,000
1,000
6
86
166
246
326
406
486
566
TIME IN MICROSECONDS AFTER PULSE

Fig. 9