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PROMPT NEUTRON DECAY AND REACTIVITY MEASUREMENTS IN SUBCRITICAL URANIUM METAL CYLINDERS

J. T. Mihalczo

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J. T. Mihalczo

FEBRUARY 1968

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PROMPT NEUTRON DECAY AND REACTIVITY MEASUREMENTS IN SUBCRITICAL URANIUM METAL CYLINDERS

J. T. Mihalczo

ABSTRACT

Prompt neutron decay constants have been determined for unreflected and unmoderated subcritical cylinders of enriched uranium (93.15% ^{235}U) by the Rossi-α technique. The cylinder diameters were 17.77, 27.94, and 38.09 cm and the heights, at these diameters, varied from 10.184 to 2.548, 8.431 to 5.399, and 7.502 to 4.780 cm, respectively. The decay constants agreed to within 4% with those measured by the pulsed neutron method; the comparison with the results of S_n transport theory calculations showed disagreements as large as 20%. Reactivities as much as 33 dollars subcritical were determined from the prompt neutron decay constant at delayed criticality and changes in the prompt neutron lifetime with cylinder height calculated by S_n transport theory. These reactivities agreed favorably with values determined by an analog computer whose input was the response of an ionization chamber to power changes when an assembly was disassembled from delayed criticality to a given reactivity.

INTRODUCTION

This report describes a series of measurements[1] performed between September 1965 and October 1966 at the Oak Ridge Critical Experiments Facility. These experiments attempted to determine whether the Rossi-α technique, previously described by Orndoff,[2] could be used to measure the prompt neutron time behavior in very subcritical, small, homogeneous assemblies of uranium and the extent to which space-independent neutron kinetics could be used to interpret such measurements. Although Rossi-α measurements have been made, usually near delayed criticality, some work has been done on subcritical systems.[4]

In these experiments the prompt neutron decay constant in subcritical unreflected and unmoderated uranium cylinders was determined by the Rossi-α technique and in some of the cylinders by the pulsed neutron method. The reactivity of the cylinders was varied by changing either or both the diameter and the height. The reactivity of some cylinders was obtained from the measured prompt neutron decay constant, the ratio of the delayed neutron fraction to the prompt neutron lifetime (β/ℓ), determined previously[5] for delayed critical cylinders of the same diameter, and the calculated changes in the prompt neutron lifetime due to variation in cylinder height. These reactivities are compared to those measured using an analog computer[6] which describes the kinetic behavior of the neutron population when the reactivity of an assembly is reduced from delayed criticality.

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1. J. T. Mihalczo, Trans. Am. Nucl. Soc. 9, 175 (1966).
2. J. Orndoff, Nucl. Sci. Eng. 2, 450 (1957).
3. G. S. Brunson et al., "A Survey of Prompt-Neutron Lifetimes in Fast Critical Systems," ANL-6681, Argonne National Laboratory (1963); A. Bergstrom, et al., "Determination of Neutron Lifetime and Reactivity in the Fast Critical FRD Assembly," Proc. of Symposium on Pulsed Neutron Research, Vol. II, 357, IAEA, Vienna (1965).
4. R. Comte et al., "Measures Par Neutrons Pulses sur des Assemblages Critiques," Proc. of Symposium on Pulsed Neutron Research, Vol. II, 337, IAEA, Vienna (1965); S. Ukai, Nucl. Sci. Tech. 2, 355 (1965); S. Ukai, S. Takeda, and S. Yamada, Nukleonik 7, 488 (1965).
5. J. T. Mihalczo, Nucl. Sci. Eng. 20, 60 (1964).
6. Cesar A. Sastre, Nucl. Sci. Eng. 8, 443 (1960).

EXPERIMENTAL

The uranium available for these experiments was enriched to 93.15 wt % in the ^{235}U isotope,[a] had an average density of 18.76 g/cm^3, and has previously been described.[5] Each assembly, with axis vertical, was built on a 0.025-cm-thick stainless steel diaphragm held in position by a 76.2-cm-ID, 2.54-cm-thick aluminum clamping ring which was supported about four meters above the floor. The cylinder diameters were 17.77, 27.94, and 38.09 cm with heights varing in 0.317 cm decrements from 10.184 to 6.367, 8.431 to 5.399, and 7.502 to 4.780, respectively. The 17.77-cm-diam cylinder was 2.548 cm high for one measurement. The dimensions of the available metal pieces resulted in small stepwise irregularities in the top surface of some of the cylinders. The dimensions of the various assemblies are given in Table 1. Columns 3 through 7 show the height of the center disc and of successive 2.54-cm-wide radial increments.

Rossi-α Measurements

Prompt neutron decay constants were determined by the Rossi-α technique in which the average time distribution of the neutron population associated with a common ancestor in a fission chain is measured. The necessary instrumentation, shown by block diagram in Fig. 1, must determine this time distribution during the intervals of the order of the mean chain length. In these experiments two detectors, A and B, sampled leakage neutrons from an assembly. Detector A was a proton-recoil type plastic scintillator[b] 5.1 cm in diameter and 1.27 cm thick; Detector B was a similar plastic scintillator half as thick. In a very limited number of measurements Detector B was a 1-cm-diam, 1-cm-high spiral fission counter containing ^{235}U. The time distribution of events detected by B with respect to the detection of an event by A was measured. Time intervals between successive signals from A and B, respectively, as short as 5 nsec could be measured by a time-interval counter[c] which used delay lines for interpolation of the basic 40-nsec period of a crystal oscillator. A PDP 4 digital computer

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[a] Other uranium isotopes were present in the following amounts: 0.97% ^{234}U, 0.24% ^{236}U, and 5.64% ^{238}U.
[b] Nuclear Enterprises Type NE 102.
[c] Eldorado Model 541.

Table 1. Dimensions of and Prompt Neutron Decay Constants in Uranium Cylinders.

Outside Diameter (cm)	Average Height (cm)	Height (cm) for Radial Increments (cm) of[a]					Uranium Density (g/cm^3)	Mass (kg of U)	Prompt Neutron[b] Decay Constant $(\mu sec)^{-1}$
		0-8.89	8.89-11.43	11.43-13.97	13.97-16.51	16.51-19.05			
38.090	7.502	7.505	7.490	7.496	7.510	7.504	18.647	159.414	4.38 ± 0.05
38.091	7.337	7.330	7.325	7.331	7.348	7.347	18.660	156.022	6.66 ± 0.08
38.090	7.016	7.018	7.002	7.015	7.021	7.021	18.667	149.243	10.86 ± 0.09
38.091	6.693	6.697	6.685	6.683	6.698	6.697	18.671	142.395	15.71 ± 0.11
38.090	6.373	6.382	6.365	6.358	6.387	6.367	18.669	135.569	20.75 ± 0.13
38.089	6.055	6.057	6.051	6.052	6.066	6.049	18.670	128.816	25.54 ± 0.38
38.090	5.734	5.733	5.730	5.726	5.745	5.732	18.679	122.036	30.51 ± 0.39
38.090	5.419	5.418	5.415	5.408	5.427	5.423	18.675	115.315	35.36 ± 0.54
38.091	5.099	5.105	5.094	5.090	5.108	5.097	18.666	108.472	40.69 ± 0.48
38.087	4.780	4.781	4.780	4.785	4.782	4.775	18.660	101.623	48.20 ± 1.20
27.929	8.431	8.433	8.440	8.422	--	--	18.670	96.545	3.22 ± 0.02
27.937	8.266	8.263	8.261	8.275	--	--	18.683	94.768	5.05 ± 0.05
27.933	8.097	8.087	8.100	8.108	--	--	18.726	92.989	6.72 ± 0.07
27.933	7.943	7.933	7.951	7.948	--	--	18.724	91.140	9.00 ± 0.14
27.935	7.641	7.638	7.645	7.641	--	--	18.673	87.441	12.86 ± 0.08
27.935	7.332	7.330	7.329	7.338	--	--	18.666	83.891	16.91 ± 0.15
27.935	7.005	7.007	7.003	7.003	--	--	18.679	80.192	20.94 ± 0.18
27.934	6.678	6.682	6.675	6.677	--	--	18.715	76.597	25.84 ± 0.18
27.933	6.356	6.360	6.356	6.351	--	--	18.717	72.904	29.96 ± 0.28
27.934	6.038	6.042	6.035	6.035	--	--	18.713	69.244	36.76 ± 0.40
27.934	5.726	5.728	5.719	5.728	--	--	18.707	65.643	40.94 ± 0.57
27.934	5.399	5.403	5.395	5.398	--	--	18.722	61.950	46.73 ± 0.72
17.771	10.184	10.184	--	--	--	--	18.734	47.325	15.44 ± 0.07
17.771	9.234	9.234	--	--	--	--	18.712	42.857	22.45 ± 0.23
17.771	8.281	8.281	--	--	--	--	18.714	38.437	30.86 ± 0.26
17.771	7.967	7.967	--	--	--	--	18.723	36.973	34.38 ± 0.25
17.771	7.642	7.642	--	--	--	--	18.729	35.499	37.04 ± 0.22
17.771	7.322	7.322	--	--	--	--	18.732	34.018	40.67 ± 0.26
17.771	7.007	7.007	--	--	--	--	18.722	32.538	44.24 ± 0.24
17.771	6.687	6.687	--	--	--	--	18.728	31.064	48.24 ± 0.32
17.771	6.367	6.367	--	--	--	--	18.732	29.583	52.89 ± 0.37

a. As indicated by the subheadings, the assemblies were constructed from 8.89-cm-radius discs and concentric 2.54-cm-wide annuli having nominal inside radii of 8.89, 11.43, 13.97, and 16.51 cm, respectively.

b. Measured by the Rossi-α technique - not corrected for the presence of the support structure and detectors. Errors indicated are one standard deviation from a least-squares analysis of the data.

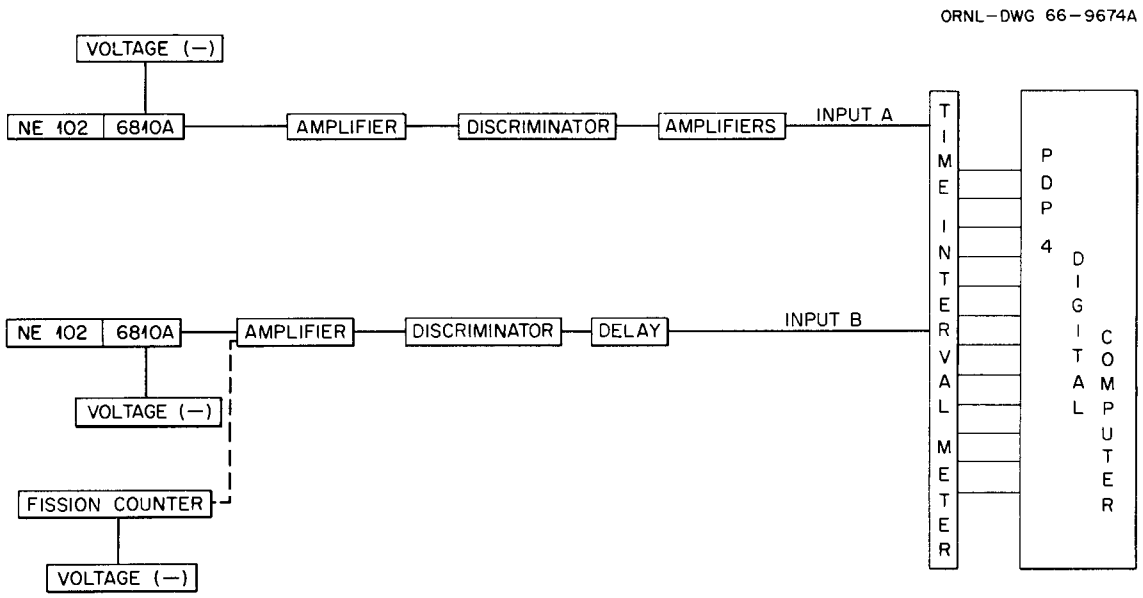

Fig. 1. Block Diagram of Electronic Circuitry for Rossi-α Measurements.

processed the binary information from the time interval counter and the composite system served as the time analyzer. The initial pulse from Detector A started a count of the 5-nsec intervals, or of a preselected binary multiple of this interval, and the succeeding pulse from Detector B stopped this count. The number of intervals thereby counted was recorded in the memory of the computer. This process was repeated until more than 2.5×10^8 fission chains were sampled by Detector A.

In the measurements a Po-Be neutron source (1.9 cm in diameter and 1.9 cm high emitting $\sim 10^7$ neutrons per second) was placed on the upper plane surface of the assembly and provided the neutrons to initiate the fission chains. The uranium was located between the source and the detectors thereby reducing the contribution of the source to the background. The detectors were located about 1.9 cm from the lateral surface of the assembly. This source-detector-assembly configuration is shown in Fig. 2.

Since the probability that a prompt neutron exists in the assembly is exponential, the probability that a fission-chain correlated event will be observed by Detector B at a time Δt after an event was observed in Detector A is proportional to $\exp(-\alpha\Delta t)$, where α is the prompt neutron decay constant. The pulses from Detector B were delayed with respect to those from Detector A so that the events in Detector B which occurred before the event in Detector A could also be observed. Events in Detector B which occur before an event in Detector A have, therefore, a distribution proportional to $\exp(+\alpha\Delta t)$. Typical data are given in Figs. 3 through 5. The data describing the time distribution of events in Detector B both before and after the event in Detector A were fitted separately by a least-squares analysis to the sum of a constant background and an exponential and established that the distribution about the event in Detector A was symmetric. This analysis also determined the extent of the region near the peak where the decay deviated from exponential. This deviation results from the resolution, ±5 nsec, of the timing system and from differences in the flight times of the neutrons to the detectors. These flight-time effects are larger for the larger diameter cylinders. Once the symmetry was established, a discontinuous least-squares analysis,

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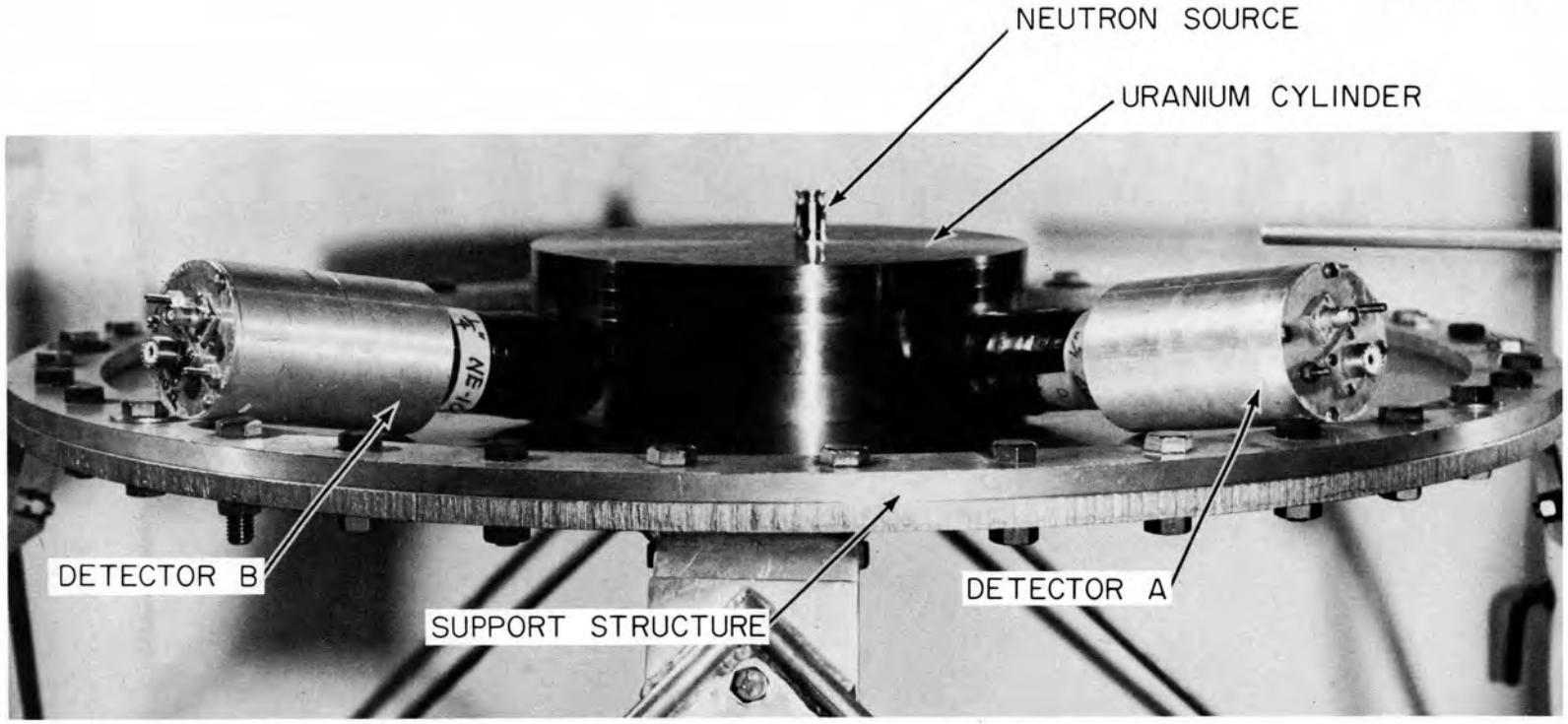

Fig. 2. Typical Uranium Cylinder Showing Location of Neutron Source and Detectors for the Rossi-α Measurements.

ORNL-DWG 67-9429

	CYLINDER HEIGHT (cm)	ORDINATE SCALE FACTOR[a]
●	10.184	0.8[b]
○	9.234	0.6
▲	8.281	2.0
△	7.642	8.0
♦	7.007	20.0

a. MULTIPLY PLOTTED POINT BY THE FACTOR TO GET DATA.

b. ABSCISSA SCALE FACTOR IS 1.5

ZERO OF TIME SET BY EVENT IN DETECTOR A.

BACKGROUND COUNTS SUBTRACTED.

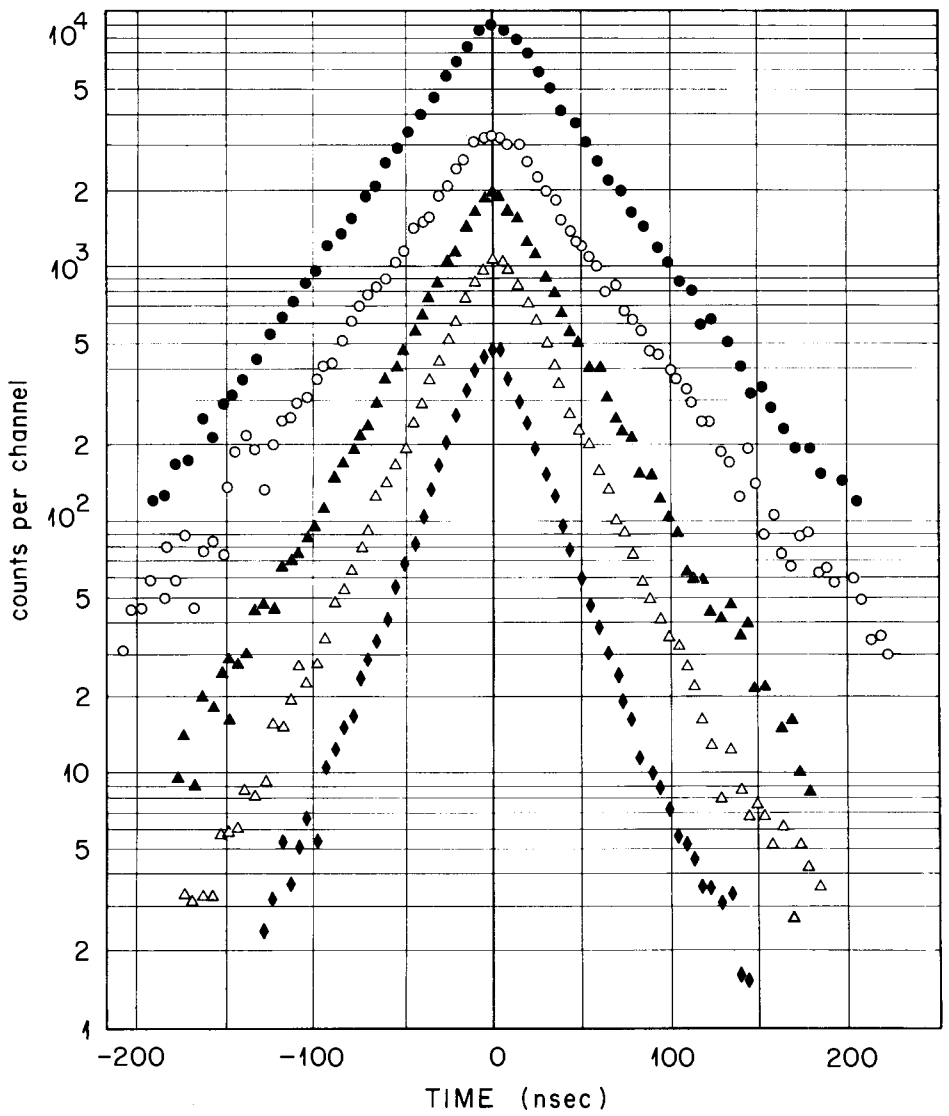

Fig. 3. Rossi-α Measurements for 17.77-cm-diam Uranium Cylinders.

ORNL-DWG 67-9430

	CYLINDER HEIGHT (cm)	ORDINATE SCALE FACTOR[a]
●	8.431	1.2[c]
○[b]	8.097	0.4
▲	7.332	4.0
△	6.678	9.0
♦	6.038	13.0
◇	5.399	70.0

a. MULTIPLY PLOTTED POINT BY THE FACTOR TO GET DATA.

b. DETECTOR B IS SPIRAL FISSION COUNTER. ABSCISSA SCALE FACTOR IS 2.

c. ABSCISSA SCALE FACTOR IS 4.

ZERO OF TIME SET BY EVENT IN DETECTOR A.

BACKGROUND COUNTS SUBTRACTED

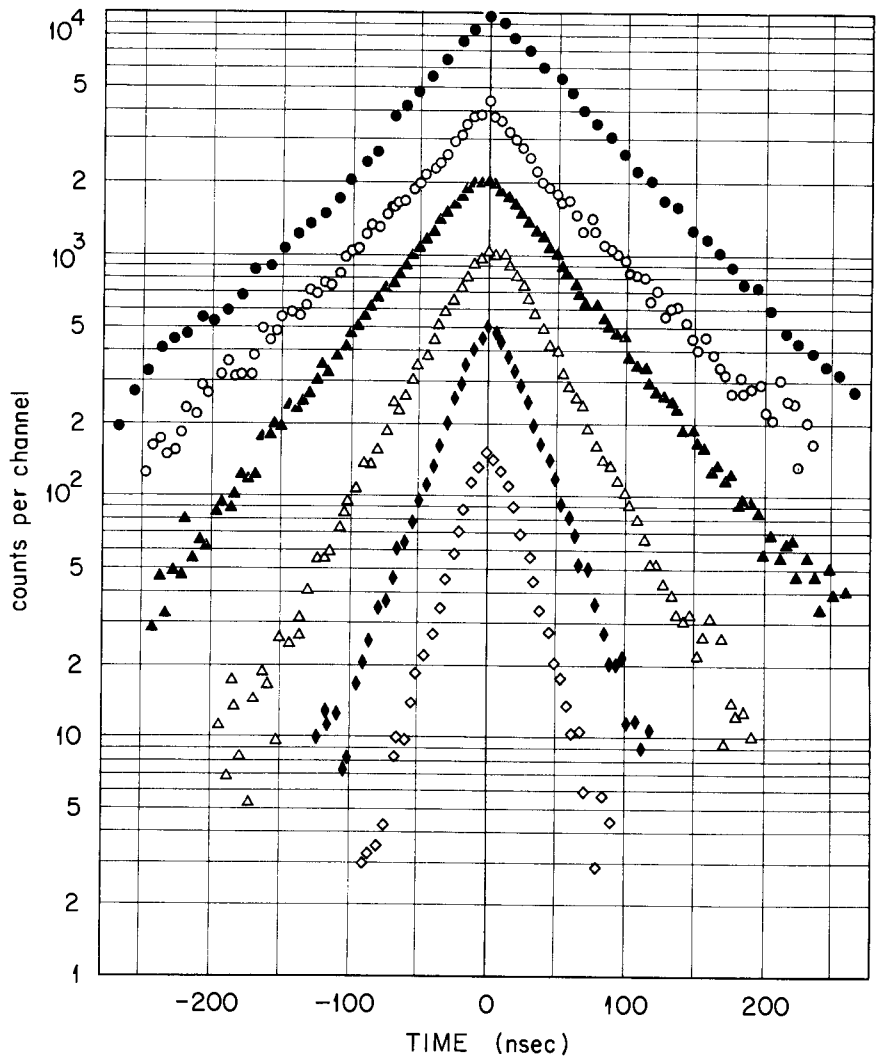

Fig. 4. Rossi-α Measurements for 27.93-cm-diam Uranium Cylinders.

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	CYLINDER HEIGHT (cm)	ORDINATE SCALE FACTOR[a]
●	7.502	0.3[b]
○	7.016	1.5[c]
▲	6.373	4.0
△	5.734	3.0
♦	5.099	12.0

a. MULTIPLY PLOTTED POINT BY THE FACTOR TO GET DATA.

b. ABSCISSA SCALE FACTOR IS 2.8

c. ABSCISSA SCALE FACTOR IS 1.35

ZERO OF TIME SET BY EVENT IN DETECTOR A.

BACKGROUND COUNTS SUBTRACTED.

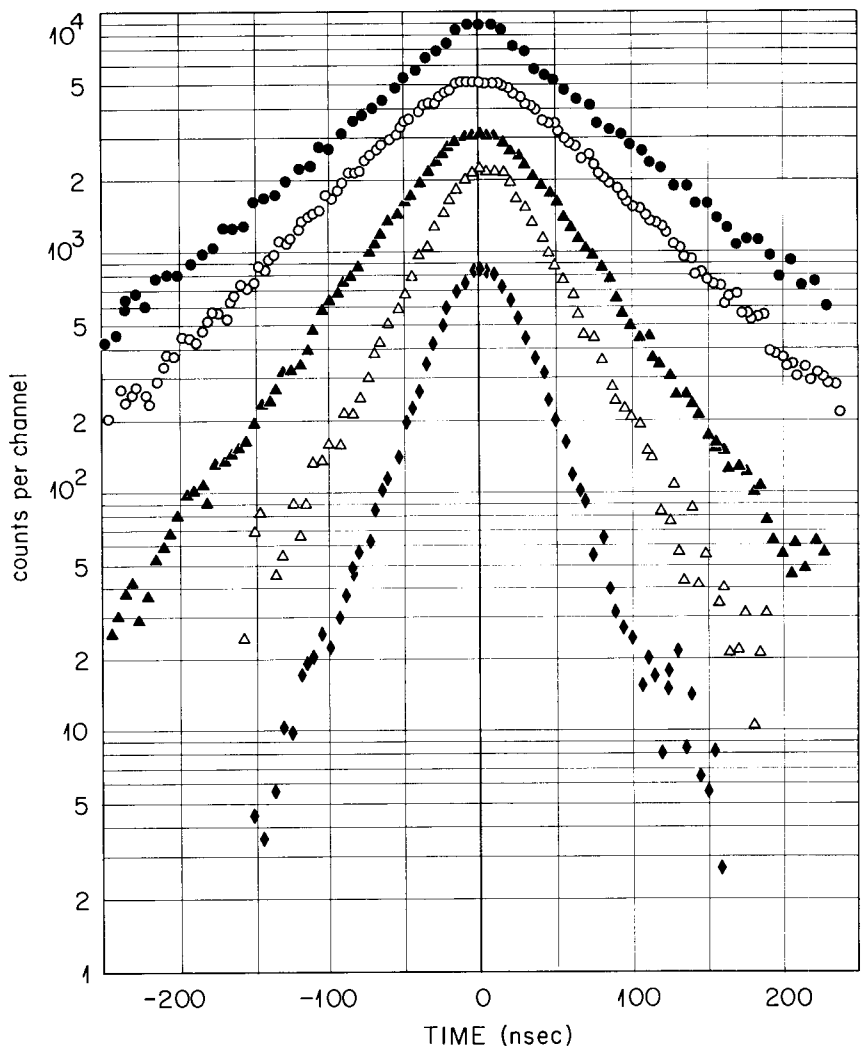

Fig. 5. Rossi-α Measurements for 38.09-cm-diam Uranium Cylinders.

which omitted the region near the peak of the distribution, fitted the data from both before and after the peak to the sum of a constant background and exponential functions having time constants of equal magnitude.

Whereas in delayed critical assemblies the initiators of fission chains are usually delayed neutrons emitted on the fundamental spatial mode, the distribution of initiators in these subcritical assemblies was primarily that of external source neutrons. On the other hand, because of the low detector efficiencies in the Rossi-α measurements, long fission chains were preferentially sampled and, on the average, have more time to reach the fundamental distribution. An analysis of the data, however, indicated that the experimental curves are single exponentials with no detectable inclusion of higher modes of decay. In this analysis successivly smaller segments of the data were examined to establish the time interval during which a single exponential decay persisted. The results are given in Table 2 for the 27.934-cm-diam, 5.399-cm-high cylinder in which the decay constant was one of the largest measured. Figure 6 shows values of the prompt neutron decay constants obtained from the least-squares analysis of data collected over various time intervals. The decay is not purely exponential from -10 to +15 nsec since the decay constant depends on how many of the data in this region are fitted. The results of the same type of analysis using the discontinuous least-squares technique, also given in Table 2, show that the total variation in the prompt neutron decay constant is 1.4%. The decay constant obtained from this discontinuous fit to the data in the time intervals from -545 to -10 and from +15 to +620 nsec is $46.8 \pm 0.5\ \mu sec^{-1}$. The results of similar analyses of data from some of the other assemblies are given in the appendix.

The measured prompt neutron decay constants and associated uncertainties are given in Table 1. The uncertainties which are one standard deviation obtained from the least-squares analysis are ±1%, on the average, with a maximum of ±2.5%.

An experiment was performed with a shorter cylinder to determine if the prompt neutron time behavior in very subcritical cylinders can be satisfactorily measured by this method. The height of the 17.771-cm-diam cylinder was decreased to 2.548 cm, which is less than one fifth of the

Table 2. Prompt Neutron Decay Constants from Least-Squares Analysis of Rossi-α Measurements on a 27.934-cm-diam, 5.399-cm-high Uranium Cylinder

Analysis of Data After Event in Detector A		Analysis of Data Before Event in Detector A		Analysis of Data both Before and After Event in Detector A[a]	
Time Interval in Which the Data Were Analyzed (nsec)	Prompt Neutron Decay Constant[b] (μsec^{-1})	Time Interval in Which the Data Were Analyzed (nsec)	Prompt Neutron Decay Constant[b] (μsec^{-1})	Time Intervals in Which the Data Were Analyzed (nsec)	Prompt Neutron Decay Constants[b] (μsec^{-1})
0 → 620	38.58 ± 0.63	0 → -545	42.19 ± 0.66	-100 → -10; 15 → 620	46.72 ± 0.46
5 → 620	42.66 ± 0.60	- 5 → -545	45.15 ± 0.60	-90 → -10; 15 → 620	46.70 ± 0.46
10 → 620	45.54 ± 0.56	-10 → -545	46.61 ± 0.71	-80 → -10; 15 → 620	46.74 ± 0.47
15 → 620	47.04 ± 0.65	-15 → -545	46.38 ± 0.86	-70 → -10; 15 → 620	46.69 ± 0.48
20 → 620	47.56 ± 0.80	-20 → -545	46.19 ± 1.06	-60 → -10; 15 → 620	46.93 ± 0.48
25 → 620	47.36 ± 1.00	-25 → -545	46.59 ± 1.32	-50 → -10; 15 → 620	46.83 ± 0.50
30 → 620	48.10 ± 1.24	-30 → -545	45.76 ± 1.62	-40 → -10; 15 → 620	47.13 ± 0.53
35 → 620	46.88 ± 1.51	-35 → -545	44.53 ± 1.95	-30 → -10; 15 → 620	46.88 ± 0.57
40 → 620	46.20 ± 1.86	-40 → -545	45.13 ± 2.44	-20 → -10; 15 → 620	47.13 ± 0.62
45 → 620	45.74 ± 2.32	-45 → -545	47.07 ± 3.1		
50 → 620	45.20 ± 2.85	-50 → -545	46.85 ± 3.9	-545 → -10; 15 → 115	46.97 ± 0.52
55 → 620	45.87 ± 3.58	-55 → -545	44.00 ± 4.69	-545 → -10; 15 → 105	46.96 ± 0.53
60 → 620	44.15 ± 4.37	-60 → -545	44.00 ± 5.84	-545 → -10; 15 → 95	46.96 ± 0.53
65 → 620	43.99 ± 5.45			-545 → -10; 15 → 85	46.88 ± 0.52
70 → 620	45.69 ± 6.98			-545 → -10; 15 → 75	46.94 ± 0.53
				-545 → -10; 15 → 65	46.84 ± 0.55
				-545 → -10; 15 → 55	46.71 ± 0.59
				-545 → -10; 15 → 45	46.48 ± 0.63
				-545 → -10; 15 → 35	46.59 ± 0.68
				-545 → -10; 15 → 25	46.60 ± 0.73

a. A discontinuous least squares method was used.
b. Error indicated is one standard deviation from least-squares analysis of data.

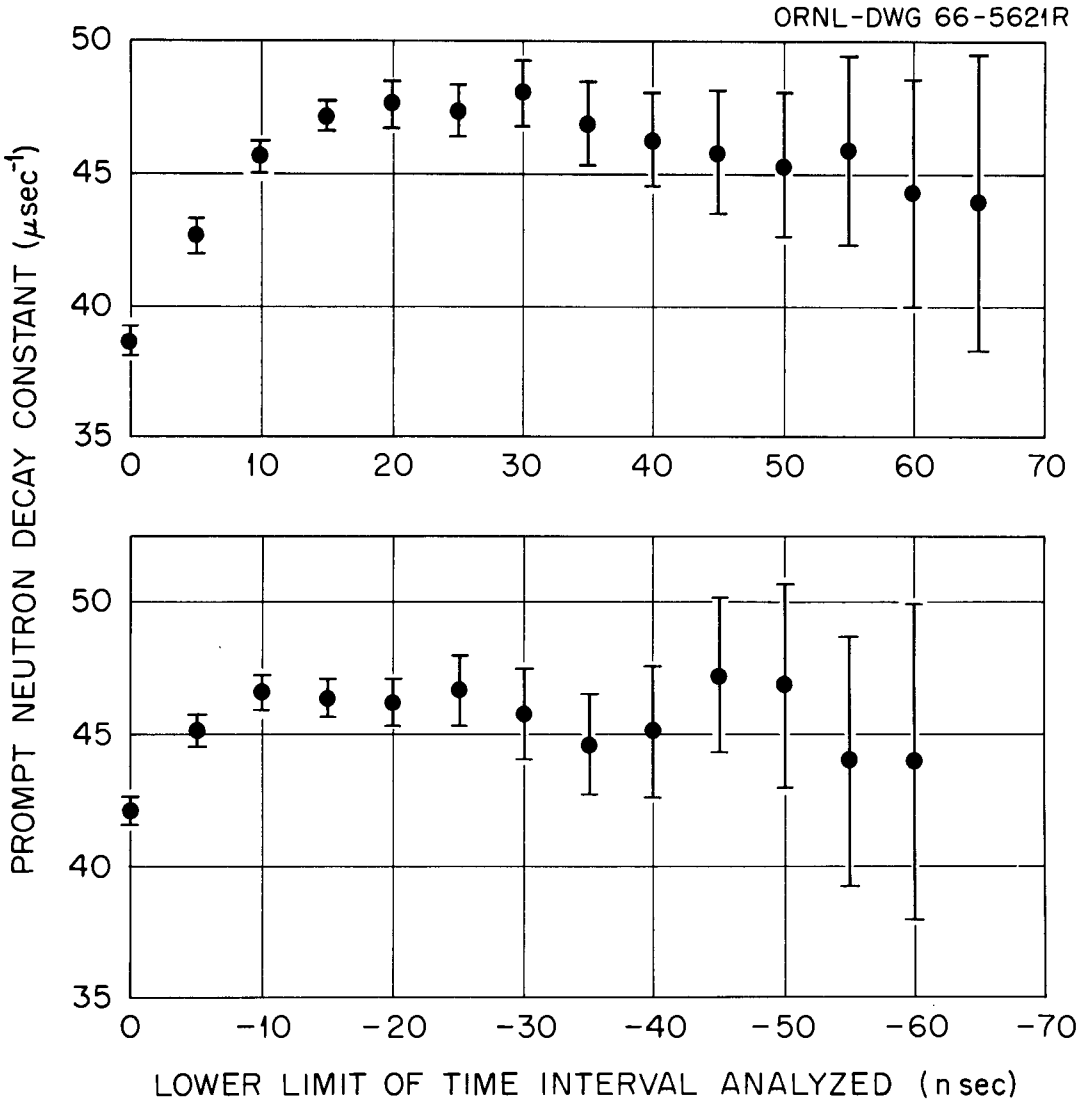

Fig. 6. Prompt Neutron Decay Constant Obtained from Rossi-α Measurement in a 27.934-cm-diam, 5.399-cm-high Cylinder During Various Time Intervals.

critical height, and the results, given in Fig. 7, indicate that a decay constant obtained from least-squares analysis of the data has a standard deviation of about 4%. The value of the constant was, however, observed to depend upon the location of the detectors.

Comparison with Pulsed Neutron Experiments

The prompt neutron decay constant in some of the cylinders was also measured by the pulsed neutron technique using a 150 kV Cockcroft-Walton accelerator which produced pulses of 14.2 MeV (d,T) neutrons, having a width at half maximum of 30 nsec and a repetition rate of 0.9 Mc. The accelerator target assembly was located on the axis of the cylinder, at distances of 10 to 20 cm from the flat surface, and the 0.635-cm-thick plastic scintillator was 2.5 cm from the other flat surface as shown in Fig. 8. The PDP 4 computer and the timing system described above served as the time analyzer. Reference pulses from the accelerator which coincided with the initiation of neutron pulse production were input B to the time interval meter (Fig. 1) and the signals from the detector were input A. The results of a typical measurement for the 27.934-cm-diam, 6.356-cm-high cylinder are shown in Fig. 9. These data were also examined by a least-squares analysis to determine the region where a pure exponential decay mode existed and the results, given in Table 3, show that the asymptotic decay begins about 170 nsec after the initiation of a neutron pulse. Measurements could not be made on cylinders with decay constants greater than about 40 μsec^{-1} because of the shape of the neutron pulse from the accelerator.

The agreement between the prompt neutron decay constants obtained by the Rossi-α and the pulsed neutron methods, shown in Table 4, indicate that the former method is applicable to measurements in subcritical fast ^{235}U assemblies.

Reactivity Measurements with an Analog Computer

An analog computer[6] solved the six delayed neutron group point kinetics equations for the reactivity as a function of time, given the neutron density in the assembly as a function of time as input. The decay constants

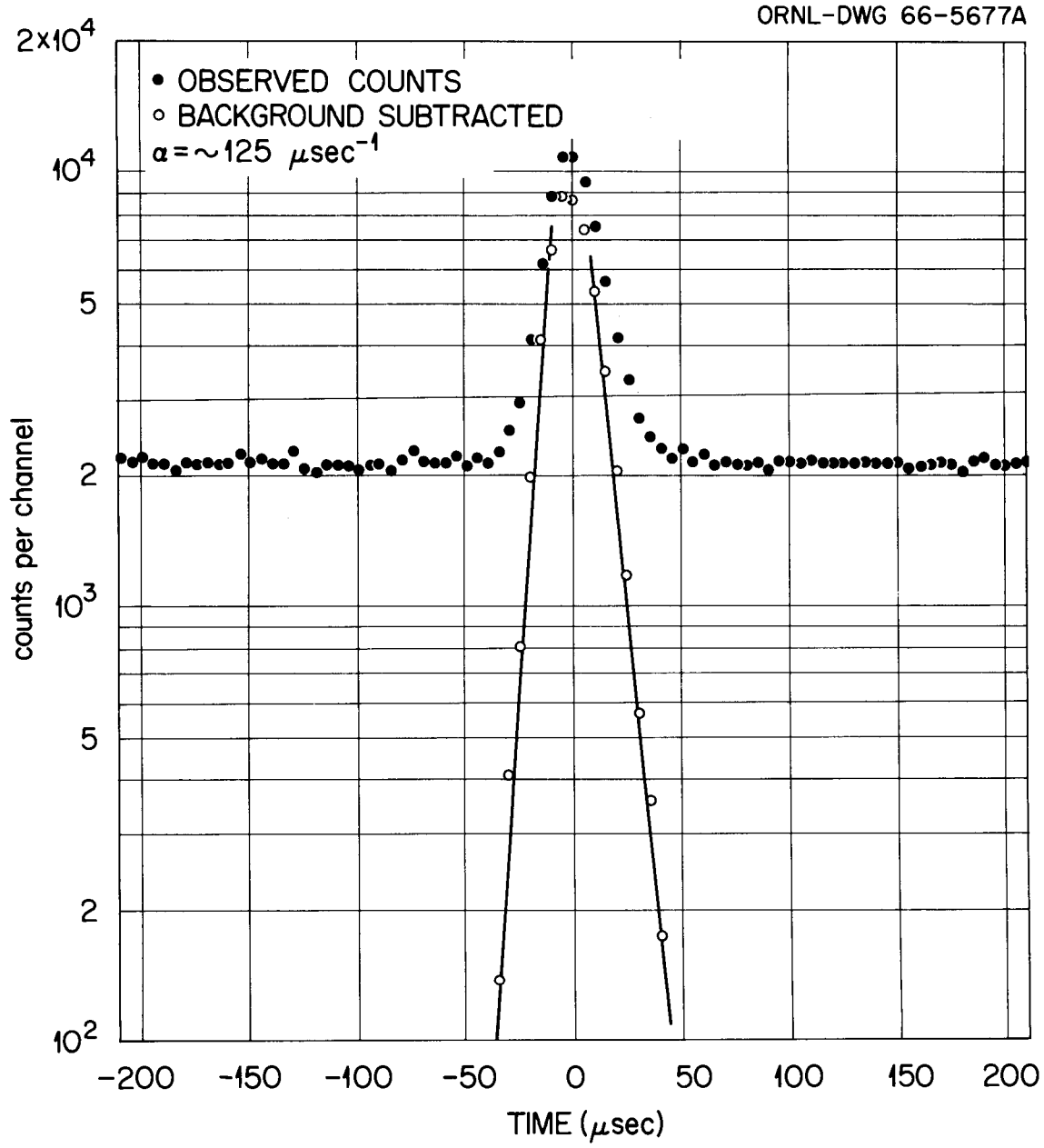

Fig. 7. Time Distribution of Fission Events in Rossi-α Measurements; 17.771-cm-diam, 2.548-cm-high Uranium Cylinder.

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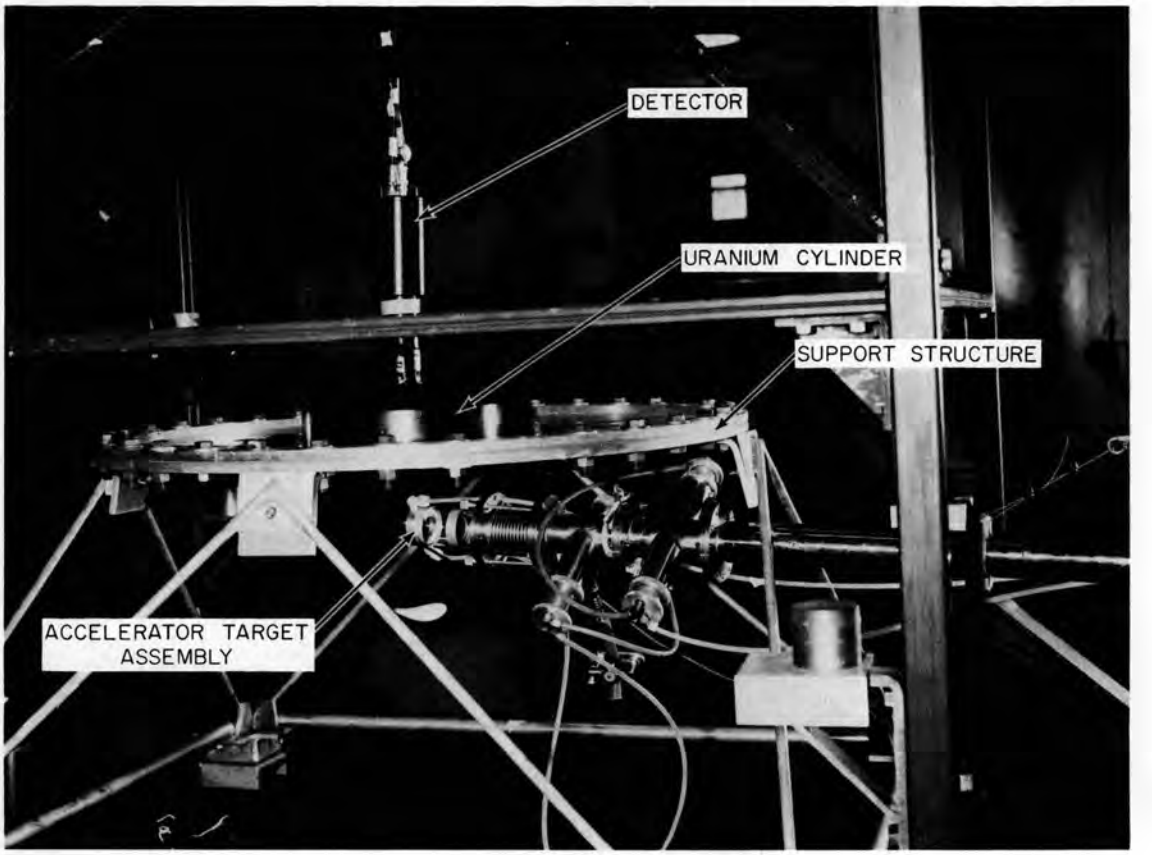

Fig. 8. Typical Location of Detector and Accelerator Target Assembly for Pulsed Neutron Measurements.

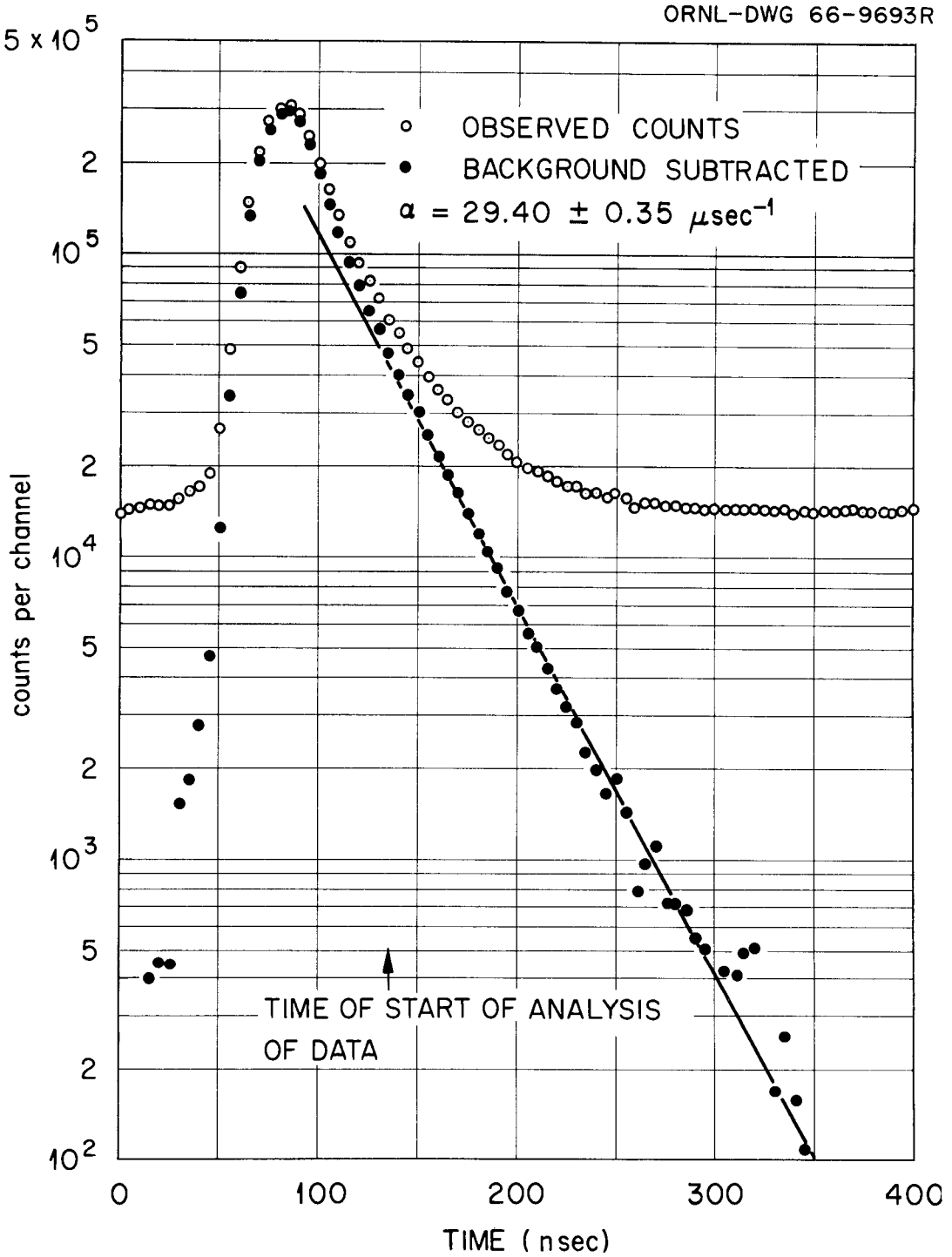

Fig. 9. Detector Response vs Time in Pulsed Neutron Measurement for a 27.934-cm-diam, 6.356-cm-high Uranium Cylinder.

Table 3. Prompt Neutron Decay Constant in a 27.934-cm-diam, 6.356-cm-high Uranium Cylinder from Pulsed Neutron Measurements

Time at Beginning of Analysis Interval[a] (nsec)	Prompt Neutron Decay Constant $(\mu sec)^{-1}$
135	30.11 ± 0.17
140	29.94 ± 0.19
145	29.96 ± 0.21
150	29.58 ± 0.23
155	29.17 ± 0.24
160	29.14 ± 0.27
165	29.31 ± 0.31
170	29.40 ± 0.35
175	29.34 ± 0.41
180	29.33 ± 0.47
185	29.54 ± 0.55
190	29.47 ± 0.63
195	28.60 ± 0.69

a. These time intervals are measured from the initiation of the neutron pulse produced by the particle accelerator.

Table 4. Comparison of Prompt Neutron Decay Constants of Uranium Cylinders Measured by Rossi-α and Pulsed Neutron Techniques

Outside Diameter (cm)	Average Height (cm)	Prompt Neutron Decay Constant[a] (μsec^{-1})	
		Rossi-α	Pulsed Neutron
38.089	6.055	25.54 ± 0.38	25.13 ± 0.20
27.933	8.097	6.72 ± 0.07	6.89 ± 0.02
27.933	7.943	9.00 ± 0.14	8.73 ± 0.02
27.935	7.641	12.86 ± 0.08	12.75 ± 0.04
27.935	7.332	16.91 ± 0.15	16.75 ± 0.06
27.934	6.678	25.84 ± 0.18	25.43 ± 0.18
27.933	6.356	29.96 ± 0.28	29.58 ± 0.23
27.934	5.726	40.94 ± 0.57	39.40 ± 0.40
17.771	10.184	15.44 ± 0.07	15.50 ± 0.07
17.771	9.234	22.45 ± 0.23	22.38 ± 0.08
17.771	8.281	30.86 ± 0.26	29.92 ± 0.20

a. Errors indicated are one standard deviation from least-squares analysis of data.

of the delayed neutron groups and the relative abundances are from Keepin.[7] The reactivity of the assemblies was determined with the analog computer in the following way: The BF_3 ionization chamber which provides the current input proportional to neutron density was placed coaxial with the uranium assembly. The distance between the center of the chamber and the center of the assembly was 119 cm. Lead, 5 cm thick and 20 cm square, was placed between the base of the chamber and the cylinder. All surfaces of the lead and of the chamber were covered with 0.1-cm-thick cadmium except the base of the chamber in contact with the lead. An aluminum or a uranium cylinder, coaxial with the fixed uranium assembly, was remotely moved toward it until the system reached delayed criticality at a given power. This cylinder was then removed 25.4 cm in 0.3 sec followed by an additional displacement of 30.5 cm in 1.2 sec. From the neutron density as a function of time, the computer determined the reactivity and listed it in digital form every 0.5 sec. The reactivity after complete removal of the cylinder was interpreted as the reactivity of the fixed assembly assuming the results are not affected by the neutron decay in the movable cylinder displaced 56 cm. Figure 10 is a photograph of one of these systems after shutdown with the cables to the chamber and the cadmium removed. The reactivities of some of the cylinders measured by the analog computer are given in Table 5.

The reactivity effect of the support structure was found to be only about 13 cents by doubling the thickness of the aluminum clamp ring and adding a stainless steel diaphragm to the top of the cylinder. The contribution to the reactivity of the neutron source and detectors was also about 13 cents.

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7. G. R. Keepin, Physics of Nuclear Kinetics, Addison-Wesley, Reading, Massachusetts (1965).

PHOTO 73137A

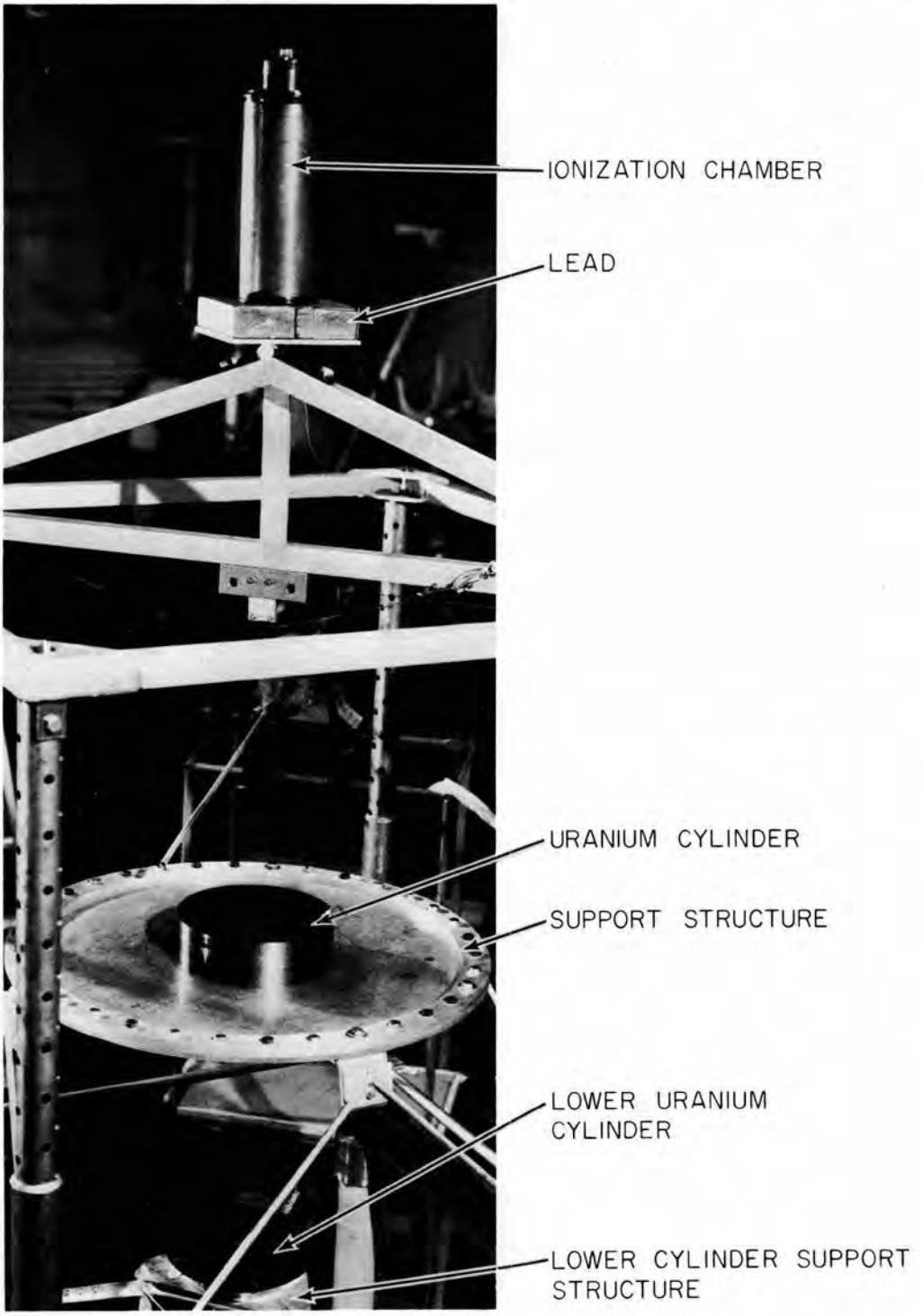

Fig. 10. Uranium Cylinder and Ionization Chamber Location for Analog Computer Measurements. The stationary cylinder whose reactivity is to be determined is on a stainless steel diaphragm, and the lower cylinder, which upon raising brings the system to delayed criticality, is mounted on an aluminum support.

Table 5. Comparison of Subcritical Reactivities of Uranium Cylinders Determined by Analog Computer and by Prompt Neutron Decay Constants

Cylinder Diameter (cm)	Cylinder Height (cm)	Subcritical Reactivity (dollars)[a]	
		From Computer[b]	From Prompt Neutron Decay Constant
38.090	7.502	2.77	3.14
38.091	7.337	4.95	5.29
38.090	7.016	9.28	9.24
38.091	6.693	13.55	13.94
38.090	6.373	18.29	18.94
38.089	6.055	22.93	23.37
38.090	5.734	28.42	28.57
38.090	5.419	33.86	33.58
27.929	8.431	2.04	2.00
27.937	8.266	3.85	3.71
27.933	8.097	5.38	5.36
27.933	7.943	7.33	7.30
27.935	7.641	11.01	11.07
27.935	7.332	15.06	14.92
27.935	7.005	19.95	18.82
27.934	6.678	24.36	23.57
27.933	6.356	28.82	27.65
17.771	10.184	13.63	13.48
17.771	9.234	22.57	20.29
17.771	8.281	32.88	28.40

a. Reactivity listed here is $(k - 1)/k\beta$.

b. The analog computer determines $(k - 1)/\beta$. A value of β of 0.00645 was used to make the conversion to $(k - 1)/k\beta$. The reactivities have been corrected for the assumption in analog computer than $\alpha = (k - 1 - \beta)/\ell$ rather than $\alpha = (k - 1 - k\beta)/\ell$. This correction is larger for the shorter cylinders but at most a 0.6% decrease in the reactivity.

Comparison of Reactivity from Prompt Neutron Decay Constants with That Measured by the Analog Computer

This section explains how the reactivity, ρ, was determined for some of the cylinders from the prompt neutron decay constant, α.

The dynamic reactivity as defined by Gross and Marable[8] is given by

$$\rho = \frac{k_d - 1}{k_d} = \frac{\ell}{Tk_d} + \sum \frac{\beta_i}{1 + \lambda_i T} \tag{1}$$

where T is the period; β_i is the delayed neutron fraction of the ith group of delayed neutrons; λ_i is the decay constant of the ith group of delayed neutrons; and ℓ is the prompt neutron lifetime given by

$$\ell = \frac{[(1/v)\ \varphi_d]}{[\nabla \cdot J_d + \Sigma_a \varphi_d]} \tag{2}$$

where the brackets mean integration over all variables; φ_d is the dynamic forward flux; v is the velocity; and Σ_a is the absorption cross section.

Since the prompt neutron decay constant α is 1/T and $\lambda_i T \approx 10^{-8} \ll 1$, Eq. (1) becomes

$$\rho = (\ell\ \alpha/k_d) + \beta \quad . \tag{3}$$

At delayed criticality $\alpha_{DC} = -\beta/\ell_{DC}$, and the reactivity can be expressed in terms of ratios of α's and ℓ's and is

$$\rho = 1 - \frac{(1 - \beta)}{[(\ell_{DC}\ \alpha_{DC}/\ell_\alpha) - \beta]} \tag{4}$$

where reactivity, ρ, is in units of dollars.

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8. E. E. Gross and J. H. Marable, Nucl. Sci. Eng. 7, 281 (1960).

The ratio of the neutron lifetime in a subcritical cylinder to that in a delayed critical cylinder was obtained using S_8 transport theory[9] and the six-group cross sections of Hansen and Roach[10] for the ^{235}U and ^{238}U to obtain the fluxes necessary to compute the values of the prompt neutron lifetime, ℓ. Fissions of ^{234}U and ^{236}U were included and the absorption and scattering properties of these isotopes were assumed to be the same as those of ^{238}U.

The ratio of lifetimes, the prompt neutron decay constants, and the multiplication factors obtained in these calculations are shown in Table 6. The calculated prompt neutron decay constants are as much as 20% larger than the experimental values with an average discrepancy of 10%. This discrepancy is consistent with previous comparisons of theory and experiment for this type of assembly.[11] Using the calculated ratio of the lifetimes and the measured values of α and α_{DC}, the reactivity was obtained from Eq. (5) and is compared to the reactivity measured by the analog computer in Table 5. The average magnitude of the reactivity discrepancy between the analog computer measurement and that obtained from the prompt neutron decay measurements is 4%.

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9. Clarence E. Lee, "The Discrete S_n Approximation to Transport Theory," LA-2595, Los Alamos Scientific Laboratory (1962).
10. G. E. Hansen and W. H. Roach, "Six and Sixteen Group Cross Sections for Fast and Intermediate Critical Assemblies," LAMS-2543, Los Alamos Scientific Laboratory (1961).
11. G. E. Hansen, "Physics of Fast and Intermediate Reactors," Proc. Seminar 1, 453, IAEA, Vienna (1962).

Table 6. S_8 Transport Theory Calculations for Uranium Cylinders and Comparisons with Measured Decay Constants

Cylinder Diameter (cm)	Cylinder Height (cm)	$\frac{\ell}{\ell_{DC}}$ [a]	Multiplication Factor	Prompt Neutron Decay Constant (μsec^{-1}) Calculated	Measured [b]
38.090	7.016	0.945	0.931	13.2	10.86
38.090	6.373	0.907	0.880	23.9	20.75
38.090	5.419	0.854	0.791	42.6	35.36
38.089	4.462	0.813	0.691	63.3	--
27.933	7.943	0.961	0.952	9.8	8.87
27.935	7.332	0.929	0.907	18.3	16.84
27.934	6.678	0.895	0.863	27.8	25.64
27.934	6.038	0.864	0.812	38.6	36.76
27.934	5.399	0.835	0.754	49.5	46.73
17.771	10.184	0.932	0.922	15.9	15.47
17.771	7.642	0.866	0.813	38.7	37.04
17.771	6.367	0.844	0.741	53.9	52.89

a. The values of ℓ/ℓ_{DC} for cylinders of other heights were obtained by interpolation.

b. Average of pulsed neutron and Rossi-α measurements if both have been made.

CONCLUSIONS

The prompt neutron decay constants in uranium cylinders obtained by the Rossi-α and the pulsed neutron method agree to within 4% with an average disagreement of 1.3% in the cases examined. Therefore, the Rossi-α method can be used to determine the prompt neutron decay constant instead of the pulsed neutron method eliminating the need for a pulsed neutron source. The Rossi-α method, although preferentially observing long fission chains which have more time to reach asymptotic decay, is sensitive to higher mode decay as the reactivity of these assemblies is decreased. Rossi-α measurements can be made for systems with decay constants as large as $\sim$50 μsec^{-1} with negligible higher mode effects and can be satisfactorily interpretated using space independent neutron kinetics. Rossi-α measurements can be made with assemblies as small as one fifth of the critical mass, having decay constants of $\sim$125 μsec^{-1}, although the measurement was influenced by the presence of higher modes and the prompt neutron decay observed depended on detector locations. The prompt neutron decay constants calculated by transport theory are as much as 20% greater than those measured with an average discrepancy of 10%. The reactivities of the subcritical cylinders obtained from prompt neutron decay constant measurements and from the analog computer agreed for negative reactivities as large as 33 dollars.

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APPENDIX

Table A1. Typical Discontinuous Least-Squares Analysis of Rossi-α Measurements for Uranium Cylinders

Cylinder Diameter (cm)	Cylinder Height (cm)	Time Interval in Which Data are Fitted (nsec)	Prompt Neutron Decay Constant (μsec^{-1})
27.93	7.33	-800 → -25; 25 → 1500	16.84 ± 0.12
		-800 → -30; 25 → 1500	16.84 ± 0.13
		-800 → -30; 30 → 1500	16.88 ± 0.13
		-800 → -35; 30 → 1500	16.91 ± 0.14
		-800 → -35; 35 → 1500	16.95 ± 0.15
		-800 → -40; 35 → 1500	16.95 ± 0.15
		-800 → -40; 40 → 1500	16.99 ± 0.16
		-800 → -45; 40 → 1500	16.95 ± 0.17
		-800 → -45; 45 → 1500	16.93 ± 0.18
		-800 → -50; 45 → 1500	16.86 ± 0.18
		-800 → -50; 50 → 1500	16.84 ± 0.19
27.93	6.67	-500 → -25; 25 → +600	25.72 ± 0.17
		-500 → -30; 25 → +600	25.84 ± 0.18
		-500 → -30; 30 → +600	25.92 ± 0.19
		-500 → -35; 30 → +600	25.97 ± 0.20
		-500 → -35; 35 → +600	25.83 ± 0.21
		-500 → -40; 35 → +600	25.86 ± 0.22
		-500 → -40; 40 → +600	25.70 ± 0.23
		-500 → -45; 40 → +600	25.84 ± 0.24
		-500 → -45; 45 → +600	25.76 ± 0.25
		-500 → -50; 45 → 600	25.78 ± 0.27
		-500 → -50; 50 → 600	25.69 ± 0.28
17.77	7.64	-500 → -15; 15 → 600	36.70 ± 0.20
		-500 → -20; 15 → 600	36.75 ± 0.21
		-500 → -20; 20 → 600	37.04 ± 0.22
		-500 → -25; 20 → 600	37.05 ± 0.23
		-500 → -25; 25 → 600	37.31 ± 0.25
		-500 → -30; 25 → 600	37.39 ± 0.26
		-500 → -30; 30 → 600	37.45 ± 0.28
		-500 → -35; 30 → 600	37.46 ± 0.30
		-500 → -35; 35 → 600	37.18 ± 0.31
		-500 → -40; 35 → 600	37.19 ± 0.33
		-500 → -40; 40 → 600	36.82 ± 0.35

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