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PROMPT NEUTRON DECAY IN A TWO-COMPONENT ENRICHED URANIUM METAL CRITICAL ASSEMBLY

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ABSTRACT

Critical experiments in which the 8 x 10 in. surfaces of two uranium (93.2 wt% U^{235}) metal slabs were separated from 0 to 5 in. have shown that the neutron flight time across the gap between the two slabs significantly affects the prompt neutron decay constant in the critical assembly. The prompt neutron decay constant, measured by the Rossi-α technique, varied from 1.07×10^6 sec^{-1} to $\sim 8.8 \times 10^5$ sec^{-1} over this separation range. Expressions for the prompt neutron lifetime in critical assemblies with large gaps are developed and a proposed calculational method is indicated. The dependence of critical slab thickness on separation of the two slabs is given.

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PROMPT NEUTRON DECAY IN A TWO-COMPONENT ENRICHED URANIUM METAL CRITICAL ASSEMBLY

INTRODUCTION

In order to understand the neutron interaction between the parts of a two component critical assembly with a single large gap it is desirable to study properties of these assemblies which depend directly on the neutrons which travel from one part to the other across the gap. One such property is the critical configuration and another is the prompt neutron lifetime defined as the average time between the birth of a neutron in fission and its disappearance from the assembly by absorption or leakage. The prompt fission neutron lifetime in a highly enriched unmoderated critical uranium metal sphere is about 6 nsec. The leakage neutrons from fast metal critical assemblies have an energy distribution similar to that of fission neutrons themselves and have an average speed of about 0.7 cm/nsec. Thus the time it takes a neutron to travel across an air gap a few centimeters wide in a critical array is a large part of its lifetime. It is expected, therefore, that the neutron lifetime will be a strong function of the size of the gap and, in addition, will depend on the fraction of the neutron population crossing the gap.

This memorandum reports experiments which have been performed to determine the magnitude of these effects and describes a calculational technique which can be used to analyze this type of experiment.

THEORY

Consider a two-component critical assembly of fissionable material in which the two parts are separated a distance x. It is required that the shape of each component be such that all leakage neutrons escape. In this assembly, composed of parts a and b, a neutron will take time t to travel from one part to the other.

Define

F_a = average fraction of neutrons born in part a,
F_b = average fraction of neutrons born in part b,
P_{ab} = probability that a neutron born in a leaks into b,
P_{ba} = probability that a neutron born in b leaks into a,
R_{ab} = probability that a neutron will be reflected by a into b,
R_{ba} = probability that a neutron will be reflected by b into a,
t_{ab} = average neutron flight time from a to b,
t_{ba} = average neutron flight time from b to a,
ℓ_s = prompt neutron lifetime in the assembly if the neutron flight time across the gap were zero.

The mean neutron lifetime can be written as

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$$\ell = \ell_s + t_{ab} F_a P_{ab} [1 + R_{ba} + R_{ab} R_{ba} + R_{ab} R_{ba}^2 + \ldots]$$

$$+ t_{ba} F_b P_{ba} [1 + R_{ab} + R_{ba} R_{ab} + R_{ba} R_{ab}^2 + \ldots].$$

Writing in series form

$$\ell = \ell_s + t_{ab} F_a P_{ab} (1 + R_{ba}) \sum_{m=0}^{\infty} R_{ab}{}^m R_{ba}{}^m$$

$$+ t_{ba} F_b P_{ba} (1 + R_{ab}) \sum_{m=0}^{\infty} R_{ab}{}^m R_{ba}{}^m$$

$$= \ell_s + t_{ab} F_a P_{ab} \frac{(1 + R_{ba})}{(1 - R_{ab} R_{ba})} + t_{ba} F_b P_{ba} \frac{(1 + R_{ab})}{(1 - R_{ab} R_{ba})} . \qquad (1)$$

If the components of the system are identical rectangular parallelepipeds, each located a distance x/2 from their plane of symmetry:

$F_a = F_b = 0.5$
$P_{ab} = P_{ba} = P(x)$
$R_{ab} = R_{ba} = R(x)$
$t_{ab} = t_{ba} = t(x)$

and the above expression is

$$\ell = \ell_s + t(x) \left[\frac{P(x)}{1 - R(x)}\right] . \qquad (2)$$

In general t, P and R will also depend very strongly on the energy and angular distribution of the neutrons and can be calculated in some special cases using transport theory and generally by Monte Carlo methods. The term (1 - R) in the denominator accounts for multiple reflections of neutrons back and forth across the gap. For a system with no gap t is zero and the lifetime is that in a single component critical assembly. As the space between the halves becomes infinite, P approaches zero faster than t approaches infinity and the lifetime again approaches that in a single component assembly.

Although equation (2) was developed for a two component critical system, it will hold for any array of identical components provided every component has the same relative position within the array. P, R and t must then be defined with respect to all components of the array.

Transport theory calculations indicate that ℓ_s varies with the geometry of the assembly. Since, however, the calculated prompt neutron lifetime in a critical sphere of 93.2 wt% U^{235}-enriched uranium differs by only about 6% from that in an infinite slab, it is expected that the correction to ℓ due to the geometry dependence of ℓ_s will be very small.

EXPERIMENTAL RESULTS

In order to verify by measurement the above effects, a series of experiments with 93.2% U^{235}-enriched uranium metal in parallelepipedal geometry has been completed. A typical assembly is shown in Fig. 1. Two 8 x 10 in. slabs of equal thickness were spaced from 0 to 5 in. The two slabs were parallel to each other and neutrons were principally exchanged by the facing 8 x 10 in. surfaces. As the gap between the halves was increased the thickness of each slab was also increased to maintain the assembly critical. The vertical motion of a hydraulically operated piston was used for remote assembly of the system to delayed critical. The lower half of these assemblies was supported by a light weight aluminum column attached to the movable piston. The upper half was supported on a 24-mil-thick stainless steel diaphragm held in tension. The effect of these support structures has been evaluated experimentally.

The prompt neutron decay constant was obtained by the Rossi-α* technique in which the average time distribution of neutrons associated with a common ancestor is measured. A detector sensitive to fission events within a chain reacting system will record counts which are nonrandom in time if the fission rate in the critical assembly is sufficiently low that there is no great overlap of fission chains. This requirement assures that the time-correlated counts are not lost in the random background due to neutrons from fission chains other than the one whose neutron population is being sampled.

Instrumentation must determine the time distribution of counts during a time interval the order of the mean chain length and the detector efficiency must be such that, at the required fission rate, statistical precision can be obtained in a reasonable length of time. Either a single detector or two detectors can be used in the experiments. With two detectors the time distribution of pulses from detector B following a pulse from detector A was observed by a Technical Measurement Corporation 256 channel time analyzer with a neutron time of flight logic unit in which sixty-four one-quarter-microsecond time channels were used. The initial pulse from detector A triggered the time of flight analyzer and succeeding counts from detector B were sorted in time. This procedure was repeated until the order of 10^7 fission chains were sampled. For unmoderated uranium critical assemblies near delayed critical, the Rossi-α measurement technique is preferable to the pulse neutron method for obtaining the prompt neutron decay constant.

A typical set of data collected in the Rossi-α measurements is shown in Fig. 2. The solid points are the observed data and the open

* J. D. Orndoff, Nucl. Sci. & Engr. 2, 450 (1957).

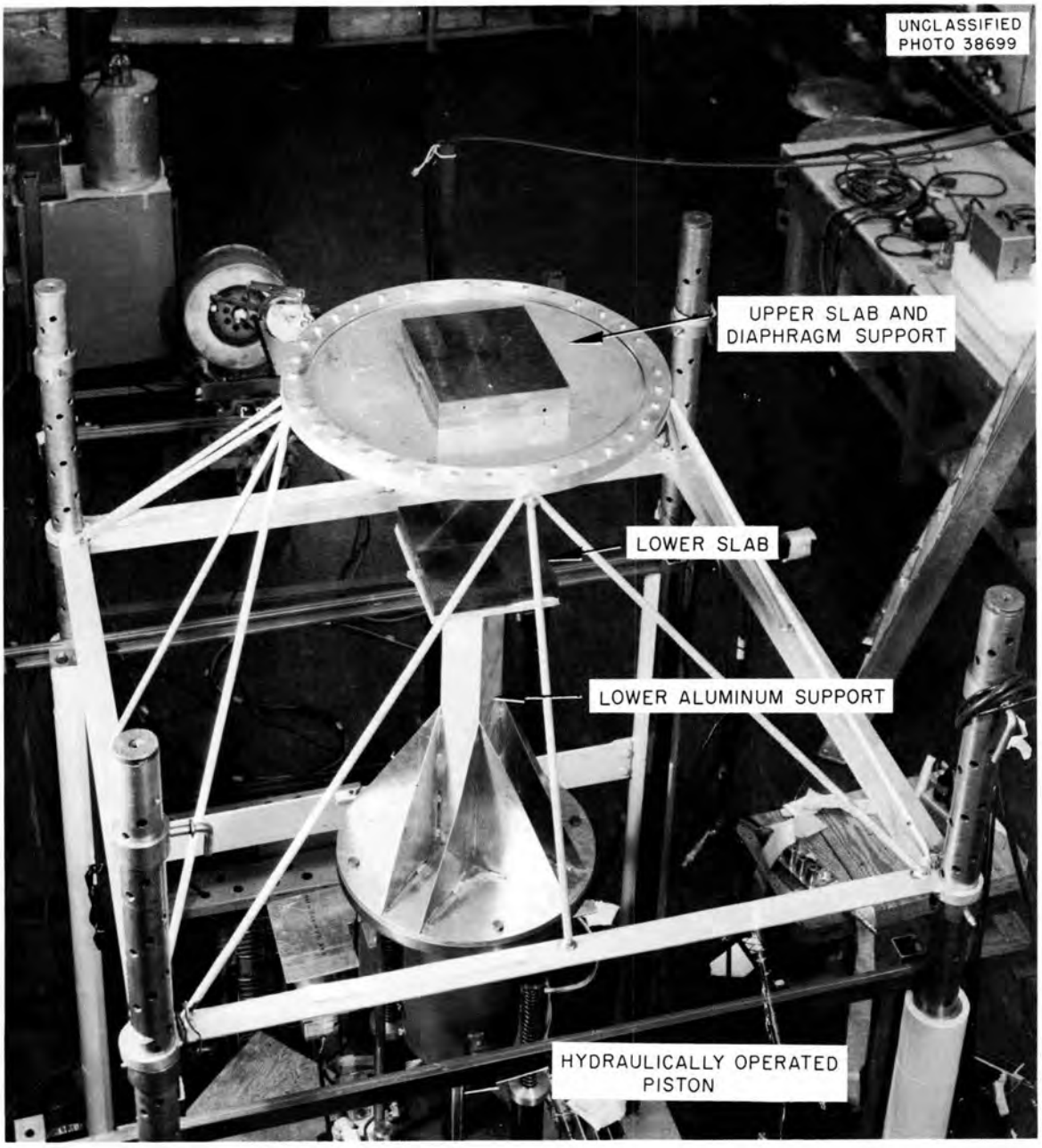

Fig. 1. Vertical Assembly Apparatus Loaded with Two 8 x 10 in. Uranium Slabs.

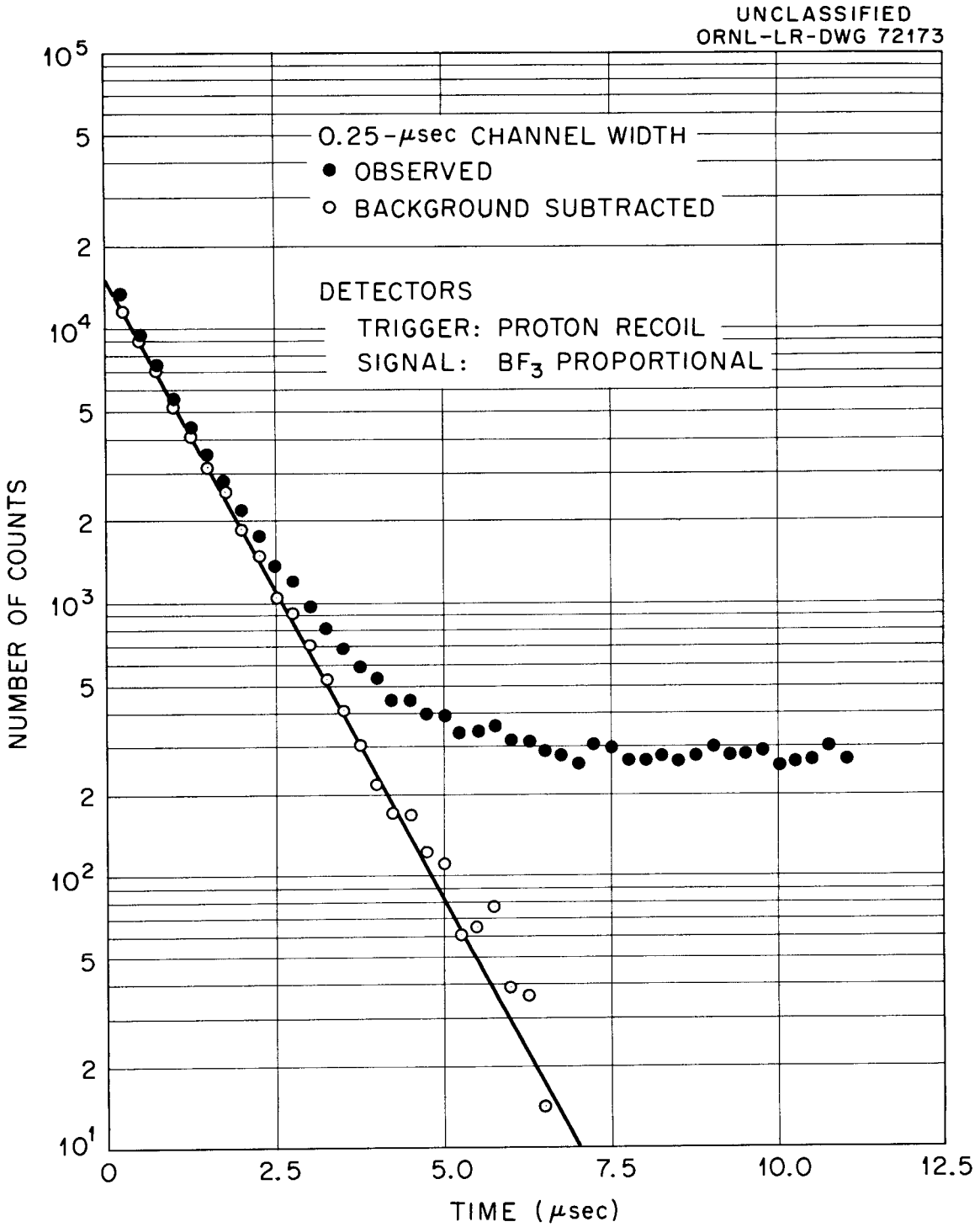

Fig. 2. Typical Detector Response as a Function of Time in a Rossi-α Measurement.

circles are the data corrected for background. For this measurement the triggering device was a proton recoil detector sensitive to both γ-rays and neutrons and the signal was from a cadmium covered 1-in.-dia BF_3 proportional counter. A least squares fit of the data was made to an exponential-plus-a-constant equation. For 10^4 counts in the peak channel the standard deviation in the decay constant is less than one per cent.

The choice of detector locations in these measurements on two component systems was investigated. If both the trigger and the signal detectors were placed at the same location in one half of an assembly in which the two parts were loosely coupled, it is not clear whether the decay of one half of the system or the decay of the entire assembly would be measured. In the limit of infinite separation a property of one half of the system would be measured. In measurements with two 8 x 10 x 2-7/8 in. slabs separated 3.3 in. the plastic scintillator used as the trigger was centered on one of the 10 x 2-7/8 in. surfaces. The spiral fission counter, used as the signal detector, was centered, successively, on one and then the other 8 x 10 in. surface of the slab adjacent to the trigger detector and on one of the 8 x 10 in. surfaces of the other slab. Variations in the results were within the experimental error.

Measurements on a solid 8 x 10 in. critical parallelepiped have also been made with a wide variety of detectors and the results are shown in Table I. The detectors were BF_3 proportional counters, a proton recoil scintillator, a LiI scintillator, a spiral fission counter and a parallel plate fission counter. The small spiral fission counter was always mounted in contact with the uranium whereas the larger detectors were positioned up to 8 in. from the assembly. It is noted that, within the experimental error, no dependence of the neutron decay constant on the type of detector or its location was observed.

Figure 3 shows the prompt neutron decay constant as a function of the thickness of one slab in a critical assembly of two identical slabs. The prompt neutron decay constant decreased rapidly from 1.07×10^6 sec^{-1} as the slab separation increased from zero to 1 in. (requiring slabs 2.25 in. thick) then remained fairly constant up to a separation of 5 in. (3.25-in.-thick slabs). It must, of course, eventually return to 1.07×10^6 sec^{-1} when the slabs are effectively infinitely separated.

The critical separation of two 8 x 10 x 2 in. slabs is about 1 cm. If the average speed of the neutrons is 0.7 cm/nsec and if all the neutrons in the assembly crossed the gap once, their average lifetime would be increased by 1.4 nsec corresponding to a prompt neutron decay constant about 20% less than were no gap present. The measured value at this separation, however, is only 10% less indicating that effectively only half of the neutrons cross the gap.

In addition to prompt neutron decay constants, these experiments evaluated the slab thickness required for criticality as a function of

Table I. Prompt Neutron Decay Constant in an 8 x 10 x 3.6 in. Critical Slab of 93.2%-U^{235}-Enriched Uranium

Detectors		Prompt Neutron Decay Constant ($sec^{-1} \times 10^6$)
Trigger	Signal	
Two 2-in.-dia BF_3 proportional counters and one fission counter	1 in. dia BF_3 proportional counter	1.075 ± 0.020
	Spiral fission counter	1.048 ± 0.032
Proton recoil scintillator	LiI	1.082 ± 0.010
	1 in. dia BF_3 proportional counter	1.075 ± 0.009
	Spiral fission counter	1.074 ± 0.009
LiI	1 in. dia BF_3 proportional counter	1.073 ± 0.012
	Average	1.075

slab separation and various reactivity effects. The results are given in Table II. The critical separation of the two 8 x 10 in. slabs as a function of the slab thickness is shown in Fig. 4. The curve has been corrected for the effects of the aluminum support for the lower slab and of the diaphragm. The former, measured by placing a mock-up of the support on the upper slab, expressed in terms of the change of the critical separation as a function of the thickness of one slab is shown in Fig. 5. The reactivity associated with the 24-mil-thick stainless steel diaphragm was measured by adding a second one to the lower slab. The reactivity change was 20¢ for all assemblies, corresponding to a change in separation ranging from 12 to 80 mils. No correction was made to the data for the reflection of neutrons by the walls and floor of the room.

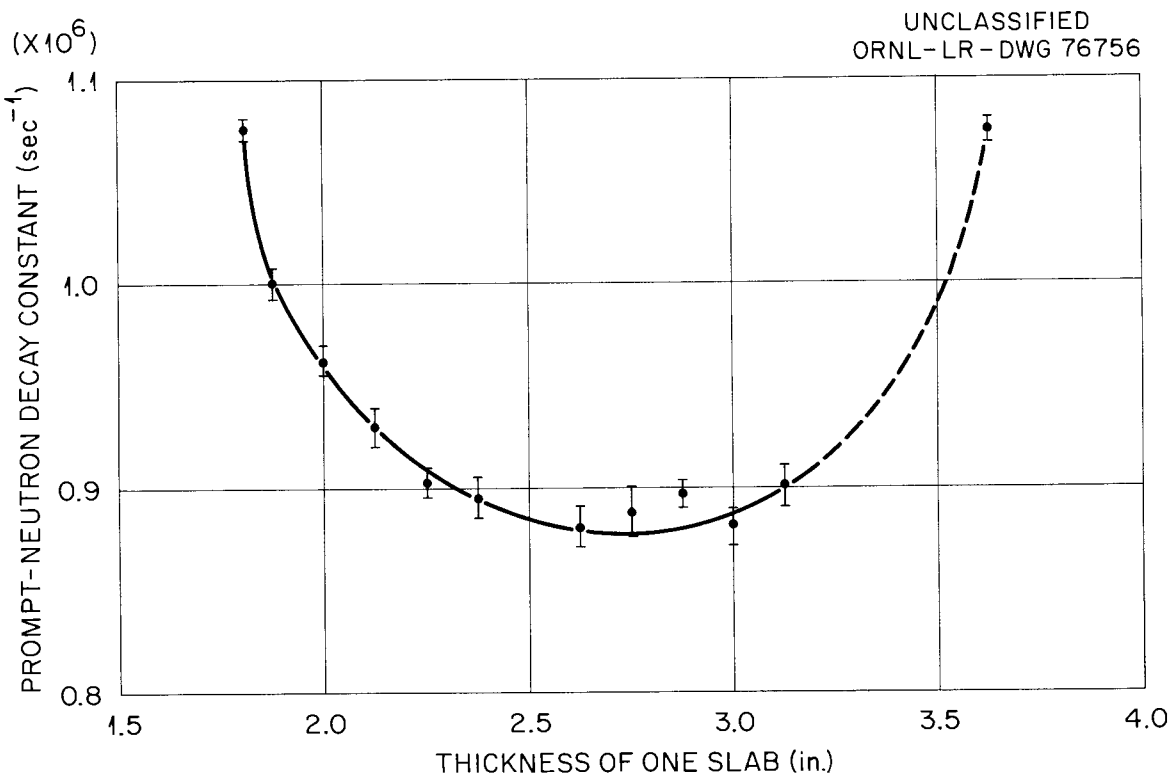

Fig. 3. Prompt-Neutron Decay Constant as a Function of the Thickness of Each Slab in a Two-Component Critical Array.

Table II. Critical Separation and Prompt Neutron Decay Constant for Various Slab Thicknesses

Thickness of Each Slab (in.)	Separation (x) Actual (in.)	Separation (x) Corrected for Support Structures[a] (in.)	$\rho/\Delta x$ (cents/mil)	Aluminum Support Worth[b] (mil)	Prompt Neutron Decay Constant[c] ($sec^{-1} \times 10^6$)
1.812[d]	-	0.000	-	-	1.075 ± 0.005 1.073 ± 0.015[e]
1.875	0.170	0.113	1.70	45	1.016 ± 0.010 0.980 ± 0.010[e]
2.000	0.443	0.384	-	46	0.962 ± 0.007
2.125	0.705	0.638	1.40	52	0.930 ± 0.009
2.250	1.013	0.935	1.24	62	0.903 ± 0.007
2.375	1.347	1.258	0.94	63	0.895 ± 0.010
2.625	2.153	2.038	0.66	85	0.881 ± 0.010
2.750	2.668	2.531	0.50	97	0.888 ± 0.010
2.875	3.302	3.142	0.45	110	0.894 ± 0.005
3.000	4.102	3.880	0.31	157	0.882 ± 0.008
3.125	5.175	4.902	0.25	211	0.901 ± 0.010

a. The correction includes the effects of both the lower aluminum support and the diaphragm.
b. Expressed in terms of the change in the critical separation of the two components.
c. The error is the standard deviation from a least squares analysis of counter data.
d. Since the two slabs are in contact corrections for the support structures were made to the slab thickness.
e. A mock-up of the support structure was added to the upper component for these measurements.

The reactivity per unit separation of the two slabs is shown in Fig. 6 where the reactivity per mil of displacement, at critical, is plotted as a function of the thickness of one slab.

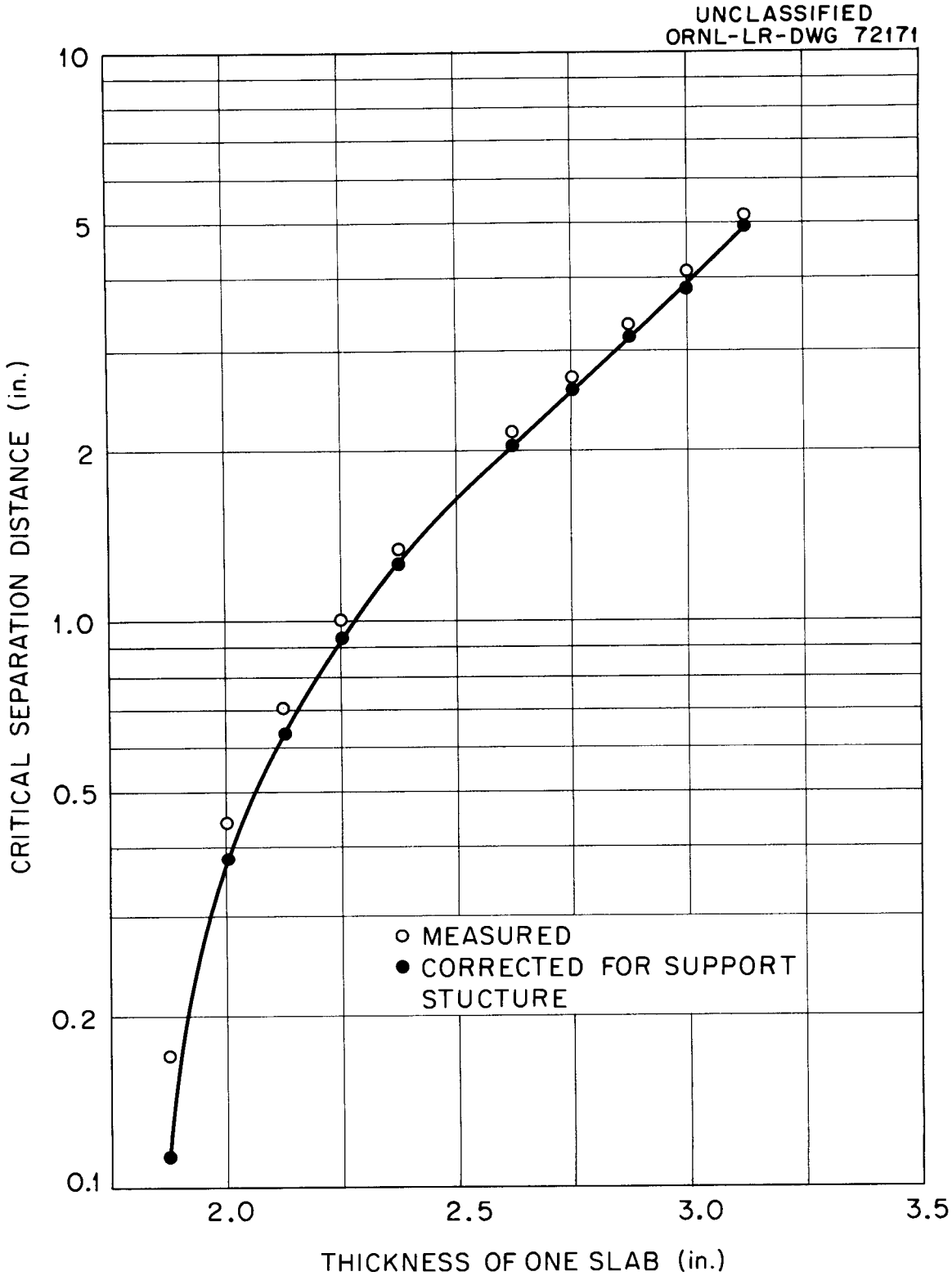

Fig. 4. Separation of the Two 8 x 10 in. Slab Components in a Critical Array as a Function of the Thickness of Each Slab.

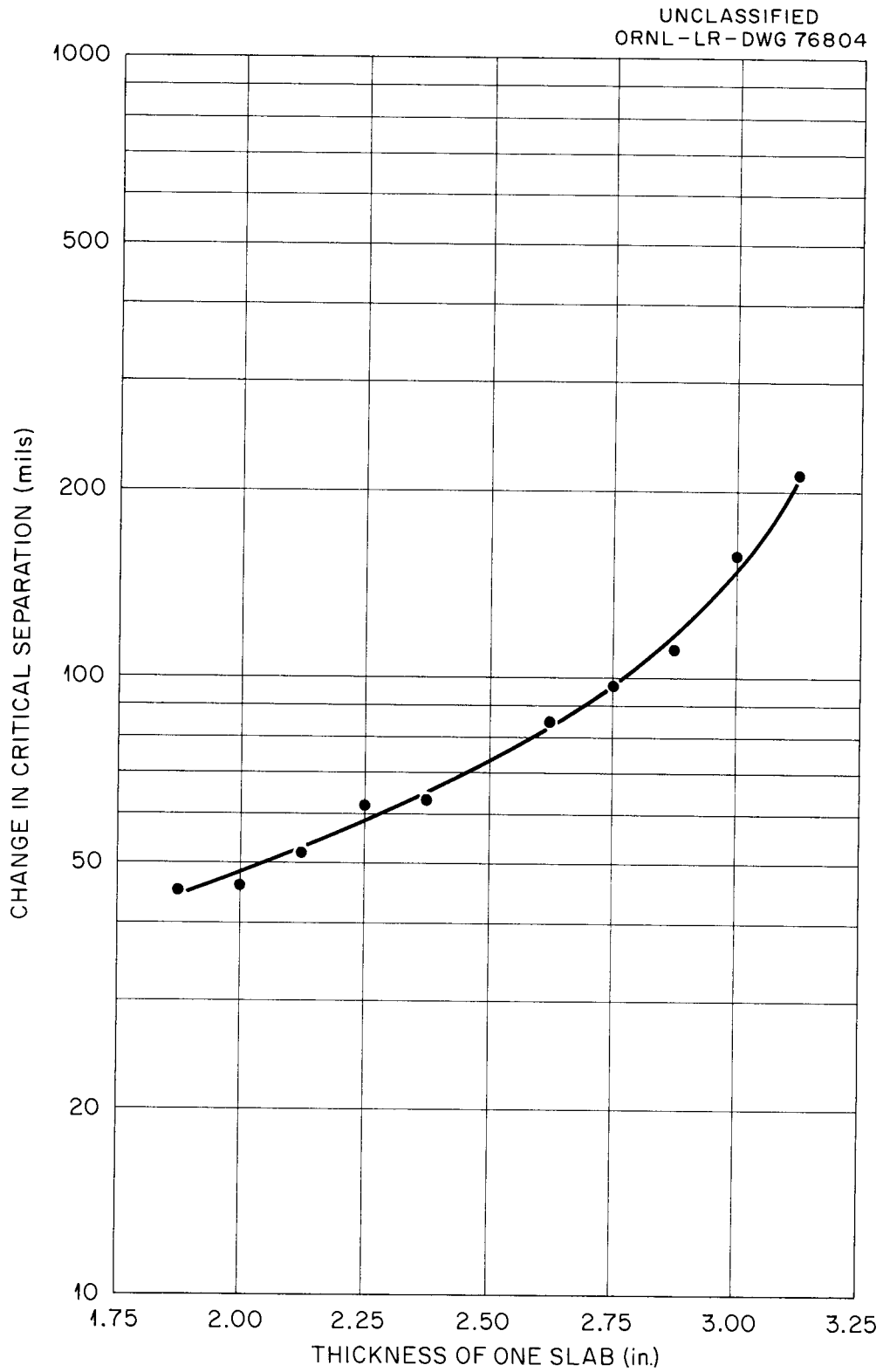

Fig. 5. Change in Critical Separation Due to the Effect of Lower Slab Support Structure vs Thickness of Each Slab.

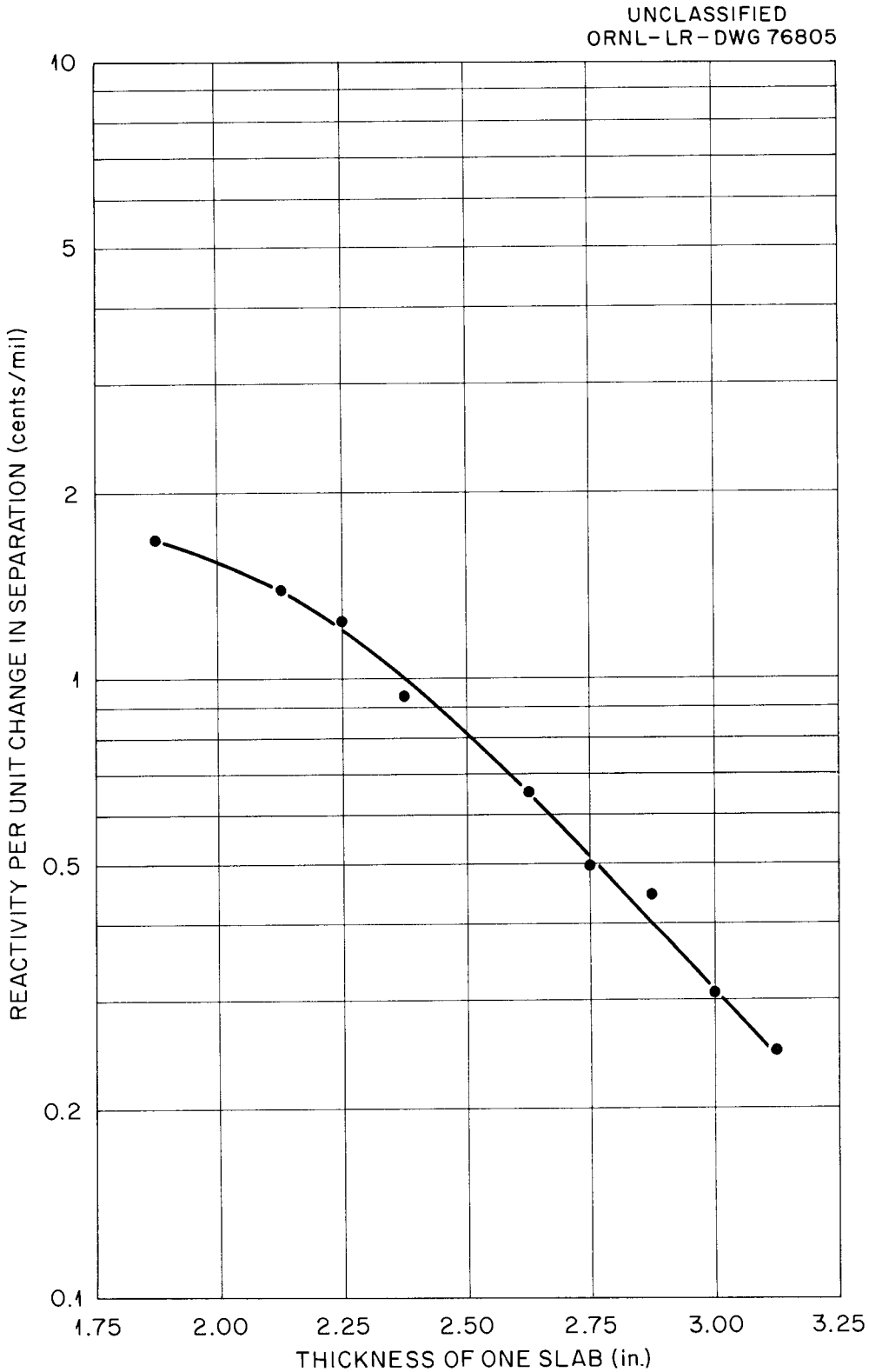

Fig. 6. Reactivity Per Unit Change in Separation of Two Uranium Slabs vs Thickness of Each Slab.

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