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CRITICAL MASS STUDIES

PART VI

BY

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SPECIAL REREVIEW
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DETERMINATION:
UNCLASSIFIED
DATE: 2/14/80

CLASSIFICATION CHANGED TO: [redacted]
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Subject Category: Criticality Hazards

CRITICAL MASS STUDIES, PART VI

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August 8, 1951

PHYSICS DIVISION
Dr. A. H. Snell, Director

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ABSTRACT

The experiments described in the following report were performed to determine safe handling conditions for P-10 alloy slugs. The data show that 90 enhanced slugs is the maximum safe number using light water as moderator and reflector. Using a mixed reflector of light water and Hanford natural uranium slugs with light water moderator, the maximum safe number of enriched slugs is reduced to 47 when the ratio of natural slugs to enhanced slugs is 108/9. For a ratio of natural slugs to enriched slugs of 38/9, the maximum safe number is 55.

Additional tests were made to confirm the nuclear safety of a proposed lead-lined shipping container when filled with enriched slugs.

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CRITICAL MASS STUDIES

PART VI

I. INTRODUCTION

Production changes at Hanford have made it necessary to increase the pile flux by the addition of slugs containing uranium highly enriched in the U-235 isotope. Certain problems of nuclear safety immediately arise. In the normal sequence of production operations, the enhanced slugs are pushed from the pile, along with their complement of natural uranium slugs, into a water-filled canal. The subsequent sorting, shipping, and storage of the enhanced slugs require further specifications as to the number that may be processed with safety under varying production conditions.

This report presents data on the conditions under which arrays of enhanced and natural uranium slugs of the Hanford type can be made critical with light water moderator, and composite reflectors of water, lead, and natural uranium. An effort was made to determine the minimum number of enhanced slugs which could be made critical under such conditions, to establish the nuclear safety of a lead-lined shipping container, and to obtain a qualitative comparison of the relative reflecting ability of lead, water, methacrylate plastic and natural uranium.

II. EXPERIMENTAL MATERIALS

The fissionable material used in these experiments was an alloy of aluminum and enriched uranium in the form of cylindrical slugs designed for Hanford. Their average dimensions and composition are given below:

TABLE I

Properties of Average Hanford Slugs

Uranium-Aluminum Alloy:	Uncanned
Length	8.00"
Diameter	1.35"
Slug Weight	542.7 gm.
Uranium Content	41.49 gm.
U-235 Content	38.71 gm.

[redacted]

TABLE I (Cont'd.)

Properties of Average Hanford Slugs

Natural Uranium: Aluminum Canned

Length	4.38"
Diameter	1.45"
Slug Weight	1827 gm.
Uranium Content	1778 gm.

The water used in these experiments as moderator and as at least partial reflector was de-mineralized and subjected to periodic analyses. A typical analysis is shown in Table II.

TABLE II

Water Analysis

Chemical Analysis

pH	7.55
Total solids, parts per million	59

Analysis of Solids

Element	Percent Present in Solids
Sodium	>10
Calcium	3
Silicon	3
Magnesium	1
Zinc	0.5
Iron	0.1
Aluminum	0.04
Copper	0.08
Nickel	0.08
Boron	0.06
Titanium	0.005
Barium	0.04
Lead	<0.08
Silver	<0.04
Cadmium	<0.04
Manganese	<0.04
Molybdenum	<0.04
Beryllium	<0.0003
Cobalt	<0.04

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TABLE II (cont'd.)

Analysis of Solids

Element	Percent Present in Solids
Chromium	<0.08
Gallium	<0.04
Hafnium	<0.5
Indium	<0.2
Tin	<0.04
Strontium	<0.06
Zirconium	<0.2

Additional materials studied as reflector were methacrylate plastic, lead, and natural uranium metal. The natural uranium used was in the form of aluminum-clad slugs, for the most part of the type used in the Hanford piles. In some experiments a few ORNL type slugs were used in the outer layers of the reflector because insufficient Hanford slugs were available. The substitution of ORNL slugs did not affect the results obtained from the experiments.

III. APPARATUS

In these experiments assemblies of slugs and other materials of interest were arranged within a tank and then flooded with water by remote control. The auxiliary equipment included a water system, control and safety devices, a movable neutron source, and instrumentation.

The flow of water, as it was pumped from the storage tanks to the reflector tank, was controlled either by a 1 1/4" or by a 3/8" solenoid valve. Fine adjustment of the level was thus possible since, by stopping the pump, the water could be drained to the storage system. The piping, storage tanks, and pump were of stainless steel. The feed valves were bronze and the 6' x 6' x 6' reflector tank was boiler plate coated with plastic paint.

A motor driven, cadmium lined stainless steel tube, 7/8" in diameter, mounted horizontally in the reflector adjacent to one face of the assembly was used as a control rod.

As a safety device, the central assembly element consisted of slugs which were mounted on a magnetically supported vertical rod. Above the slugs were placed a section of Plexiglass 8" long and a piece of stainless tubing containing cadmium. Upon deenergizing the magnet this composite fell under gravity thereby removing uranium from the array and putting

cadmium in its place. The magnet could be deenergized manually, by a power failure, or by high level radiation at either of three of the radiation detectors. The rod could be positioned by a motor driven screw jack. As a further safety measure, the reflector and moderator water could be emptied, by gravity, into the storage tank through a short length of 4" pipe normally closed by a cone shaped plug. This plug was held in place by a pair of electromagnets which were deenergized simultaneously with that supporting the safety rod.

A source of about 10^7 neutrons/sec, encased in a brass capsule, was attached to a 1/4" diameter aluminum rod 6' long. The rod was normally positioned by an electric motor drive, and supported by an electromagnet. On deenergizing the magnet, a counterweight pulled the source out of the assembly into a cadmium-lined paraffin-filled box.

Assemblies were built on a 42" square Plexiglass table having a 1" thick top supported by 1" thick vertical sheets of plastic. These sheets interlocked to form 6" square sections. The top of the table was 11" from the base of the tank. It was necessary to build the table in this manner to provide sufficient strength to support several tons of natural uranium and lead. The slugs were positioned, with their axes vertical, by a crisscross of horizontal Plexiglass strips occupying only a small fraction of the moderator volume. A view of an array in place is seen in Fig. 1.

The instrumentation was similar to that used previously[1] and consisted of boron-10 lined proportional counters with associated amplifiers, scalers, and registers for neutron detection and multiplication determinations; BF_3 ion chambers feeding DC amplifiers and Brown recorders to indicate relative radiation levels; a vibrating-reed electrometer, the output of which was recorded on a Speedomax, to show gamma intensity. There were added for these experiments a third counting system, using a boron-10 proportional counter which fed a 1024 scaler; a second vibrating-reed electrometer with an ion chamber filled with BF_3 for neutron detection; a modification of the rapid response scintillation counter and its alarm circuit to facilitate operation from the more remote location of the new control system.

All equipment could be remotely operated from the control room where the positions of the source and the control and safety rods were indicated by selsyns. The water reflector height was measured in a calibrated sight glass. A photograph of the control equipment and instrumentation is shown in Fig. 2.

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[1] Beck, C. K., D. Callihan, J. W. Morfitt, R. L. Murray, "Critical Mass Studies, Part III," Carbide and Carbon Chemicals Company, K-25 Plant, K-343, April 19, 1949.

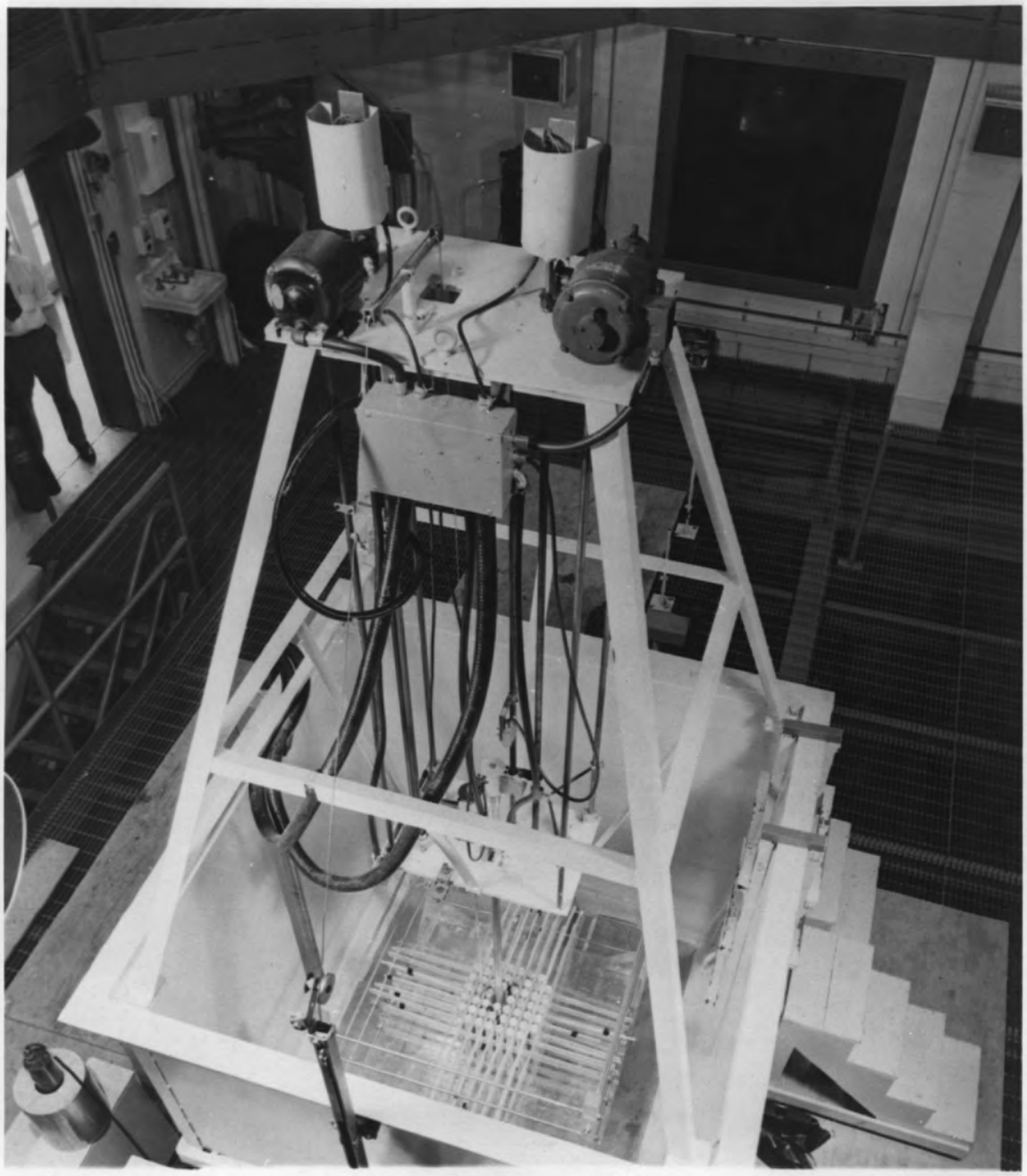

FIGURE 1

FIGURE 2

IV. EXPERIMENTAL PROCEDURE

In a typical experiment, slugs and the solid reflector, if one were under study, were stacked upon the plastic table with no water in the tank and in such quantity that the multiplication of the source neutrons was low. In most cases the slugs were arranged so that the interior ones had four coplanar nearest neighbors, a configuration which will be subsequently referred to as a square lattice. An arrangement is shown in Fig. 1.

Reflector and moderator water was then added by remote control. From time to time during the course of this addition a neutron count was taken, the first with water at the base of the assembly. Extrapolation of the usual reciprocal multiplication curve gave a reasonable prediction of the water height in the tank at criticality. In non-critical systems the maximum reciprocal multiplication had interpretable significance because the counters were mounted directly under the tank so that addition of water beyond the initial point did not add absorber between the source of neutrons and the counter. Since, in general, the results desired were the conditions under which an array was critical when fully reflected, it was frequently necessary to drain the water, change the number of slugs in the array and repeat the experiment.

V. SUMMARY OF EXPERIMENTAL RESULTS

The purpose of these experiments was to determine the minimum number of enhanced uranium-aluminum alloy slugs which could sustain a nuclear chain reaction with water moderator and with reflectors of water, water and lead, and water and Hanford natural uranium slugs, in order to provide bases for handling and storage specifications. The significant results are summarized here.

1. Maximum safe number of P-10 slugs with water reflector: 90

2. Maximum safe number of P-10 slugs with reflector of water and Hanford natural uranium slugs:
   a. When the ratio of natural to enhanced slugs is 108/9: 47
   b. When the ratio of natural to enhanced slugs is 38/9: 55

3. Nuclear safety imposes no limit on the number of P-10 slugs that can be placed within the lead-lined shipping cask described by drawing #AEC-HOO-1001. The maximum neutron multiplication of 3.3 was measured when 64 P-10 slugs were stacked in an 8 x 8 x 1 square array on 1.73 ± 0.06" centers.

4. A lead reflector, 4" thick or more, and surrounding the core of slugs on all sides, would be expected to lower the critical mass of a completely water flooded array by 5 to 7%.

5. Maximum safe number slugs with water reflector in a single tier: 142

6. An effectively infinite reflector for the arrays was 15 cm of water.

7. 400 close-packed enhanced slugs in a square lattice were not critical when flooded. When the slugs were arranged in a single tier the neutron multiplication was 2.5, in a double tier the neutron multiplication was 3.3.

8. Five close-packed, single-tier square lattices of 77 slugs each were symmetrically spaced as shown in Fig. 3 on the plastic table and completely flooded with water. The system was not critical, the neutron multiplication being less than 1.05. These experimental conditions are more favorable for interaction than those currently specified for storage of the slugs at the Idaho Chemical Processing Plant.

9. There was no significant difference in neutron behavior found between commercial methacrylate plastic and water when they were used either as a neutron reflector or moderator in the thermal systems tested.

VI. DISCUSSION OF RESULTS

Introduction

It is appropriate to discuss some of the experiments in which the results listed in the preceding section were obtained. In addition, it was also necessary to perform experiments to insure that the data obtained represented true minima and to measure the reproducibility of the experiments. Some comparative reflector data are also discussed briefly.

Studies with Water Moderator and Reflector

In the initial experiments, uniformly spaced lattices of whole slugs one and two tiers high, with axes vertical, were constructed, the slugs in the latter being colinear. The number of slugs required to make a single or a double-tiered array critical, when completely water moderated and water reflected, was determined as a function of the edge to edge separation of the slugs. In the majority of experiments the vertical separation between tiers was 0.25". Typical results are given in Table III

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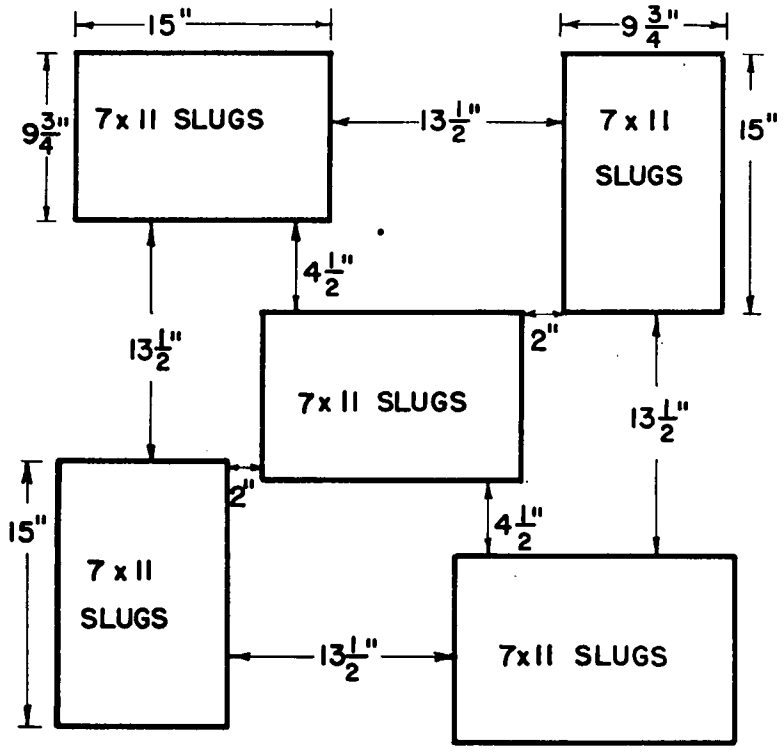

FIGURE 3. EXPERIMENTAL ARRAY FOR INTERACTION EXPERIMENT

below and presented graphically in Figs. 4 and 5. The critical number of slugs reported is interpolated from the experimental conditions existing in critical and near critical systems. The arrays in each case were square or rectangular.

TABLE III

Critical Number of Enhanced Slugs in Water Moderated and Reflected Square Lattices as a Function of Slug Separation

Slug Spacing Edge-to-Edge (inches)	Slug Spacing Center-to-Center (inches)	Critical Number Slugs Single Tier	Critical Number Slugs Double Tier
0.00	1.35	>400	>400
0.25	1.60	217	—
0.38	1.73	162	117
0.50	1.85	150	110
0.63	1.97	162	103
0.75	2.10	215	110

The slug spacings are correct to ± 0.06"

By rounding the corners of the single and double-tier arrays to form pseudocylinders, the minimum number of whole slugs which could be made critical in a uniform lattice was found to be 143 and 101, respectively. It is of interest to note that the minimum critical number of water moderated and reflected P-10 slugs in a single tier was estimated from an earlier experiment[2] to be 150 ± 30.

The curves exhibit the typical flat minima of homogeneous assemblies.[1] If one regards the increasing separation of the slugs as equivalent to dilution of a homogeneous fuel with concomitant change in the H:U-235 ratio, it can be seen that the behavior of these arrays closely parallels that of the homogeneous systems. The existence of these minima has the practical virtue of demonstrating that no critical moderation has been overlooked in the performance of the experiments. The graphs show that the minimum critical mass occurs at an H:U-235 ratio of approximately 160 in the case of the single tier and of about 200 for the double tier assembly. The H:U-235 ratios were obtained from the mass of uranium and the volume of water contained within the core. For homogeneous systems the minimum mass occurs at an H:U-235 of about 325. Neutron absorption by the aluminum and the excessive leakage of neutrons due to the high neutron age of the alloy both tend to displace the minima towards lower moderations. The observed fact that the minimum for the single tier occurs at a lower moderation than the double tier of better geometry is also expected.

[2]Callihan, D., J. D. McLendon, J. W. Morfitt, "Criticality Test on P-10 Alloy Slugs," Carbide and Carbon Chemicals Company, K-25 Plant, K-644, July 11, 1950.

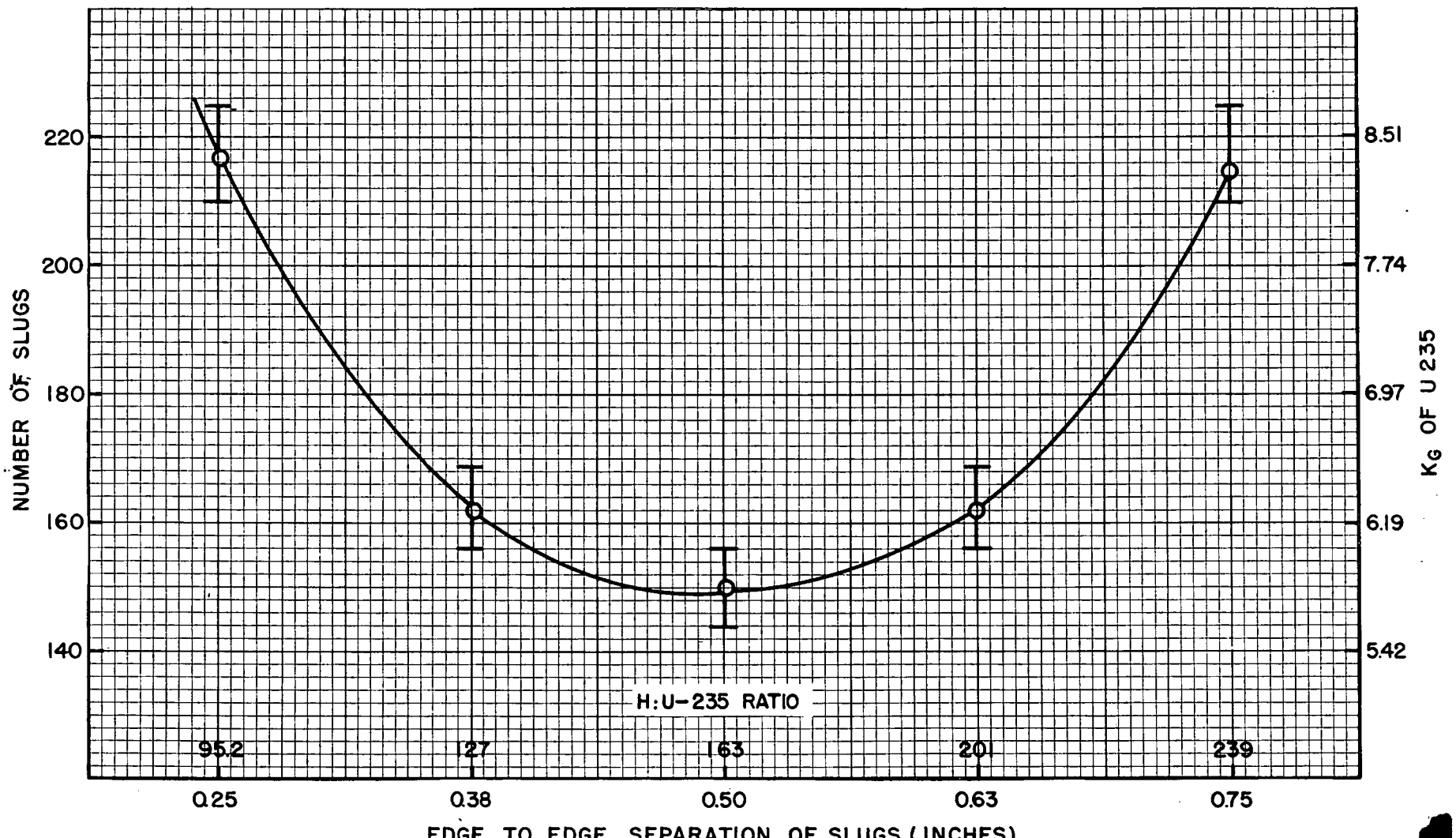

FIGURE 4. NUMBER OF SLUGS vs EDGE TO EDGE SEPARATION SINGLE TIER

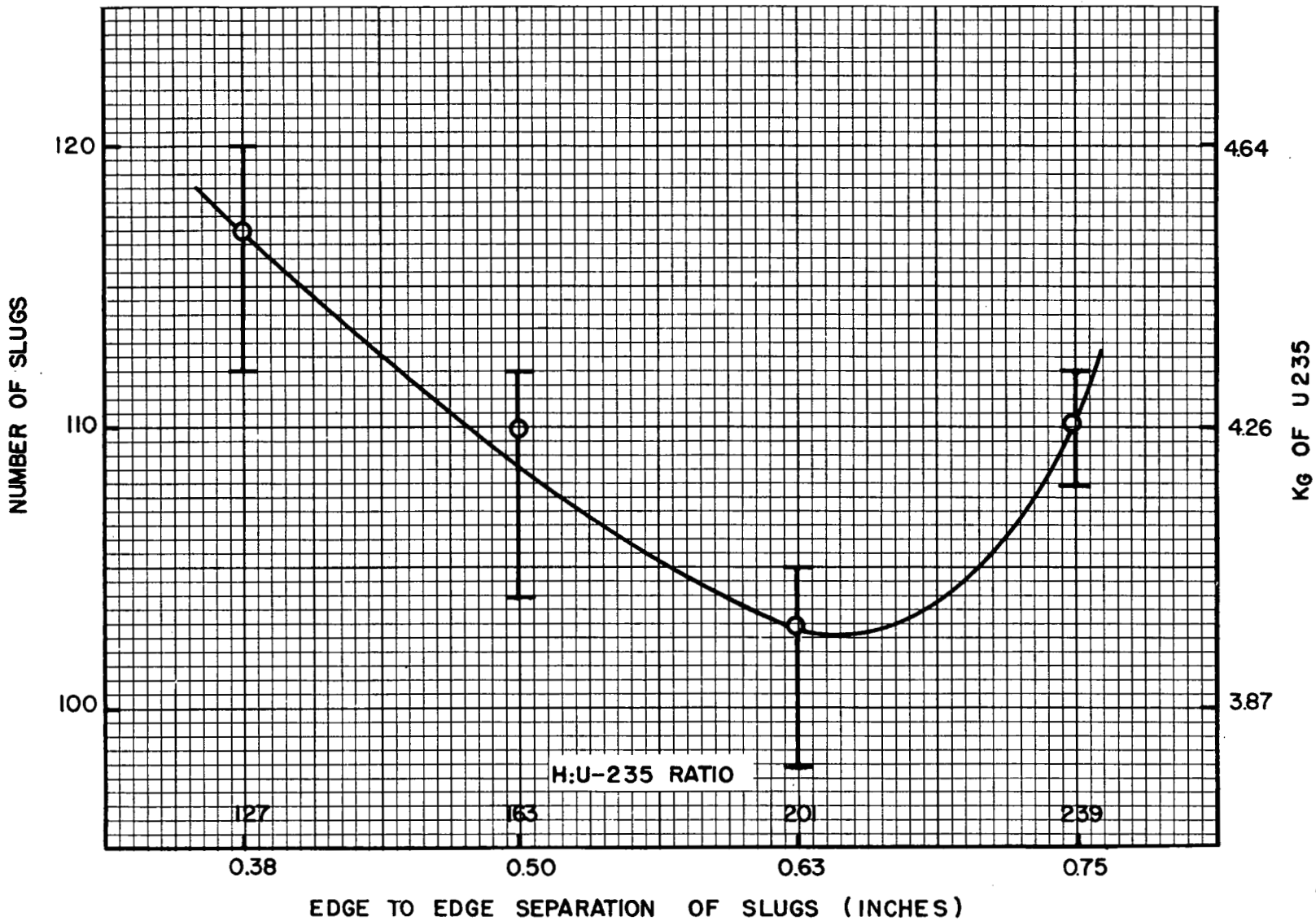

FIGURE 5. NUMBER OF SLUGS vs EDGE TO EDGE SEPARATION DOUBLE TIER

In Table IV the critical masses experimentally determined with the slugs are compared with those expected were the hydrogen and the uranium homogeneous. It was prepared in the following way. From the experimentally found critical dimensions, the H:U-235 ratio at which a water reflected homogeneous aqueous core would become critical was estimated using an adaptation of a method described previously.[3] An attempt was then made to correct the H:U-235 ratio for the effect of the aluminum both as an absorber and as a scatterer. From the corrected H:U-235 ratio and the volume of the critical array, the mass, M_H, of a homogeneous system containing the same aluminum to uranium ratio as the slugs was calculated and compared with the actual critical mass, M_E, of the alloy. The difference between the two masses is, therefore, due to inhomogeneity and concomitant higher core leakage. Details of the method are given in the Appendix.

TABLE IV

A Comparison of the Critical Masses of U-235 in P-10 Alloy Slugs and in Corresponding Homogeneous Cores

Slug Spacing Edge-to-Edge (inches)	Mean H:U-235	Experimental Mass(kg) M_E	Homogeneous Poisoned Mass (kg) M_H	M_E/M_H
		A. Single Tier		
0.00	35	>15.4	—	5.40*
.25	95	8.40	2.58	3.26
.38	125	6.27	2.27	2.76
.50	165	5.81	2.38	2.44
.63	200	6.27	2.79	2.25
.75	240	8.32	3.94	2.11
		B. Double Tier		
0.00	35	>15.4	—	4.77*
.38	125	4.53	1.27	3.56
.50	165	4.26	1.31	3.24
.63	200	3.99	1.32	3.02
.75	240	4.26	1.46	2.91

*Extrapolated value from Fig. 6.

Fig. 6 is a plot of M_E/M_H versus the edge-to-edge separation of slugs. Each set of points lies on a hyperbola whose equation is given in the

[3] Schuske, C. L., J. W. Morfitt, "An Empirical Study of Some Critical Mass Data," Carbide and Carbon Chemicals Company, Y-12 Plant, Y-533, December 6, 1949.

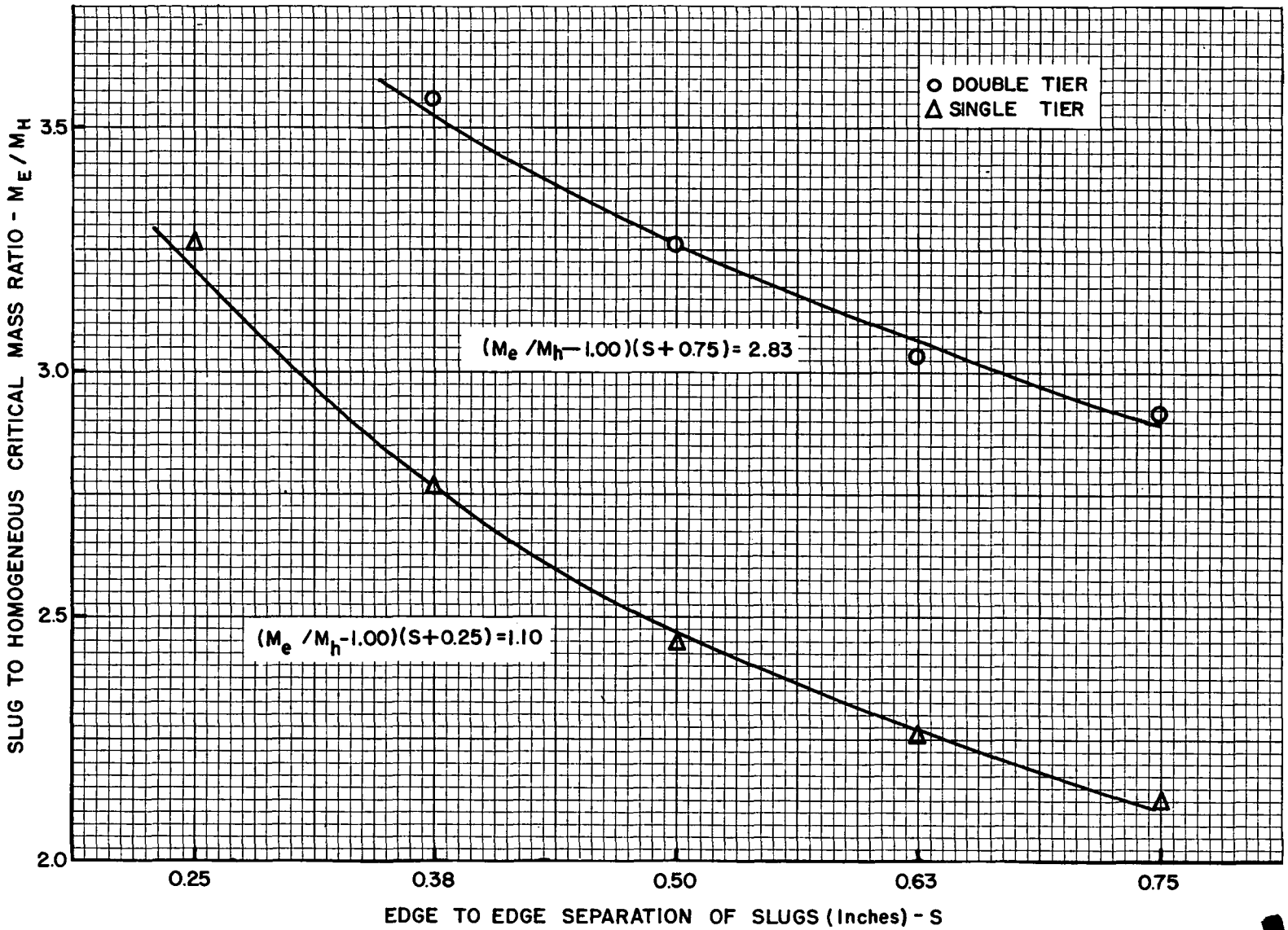

FIGURE 6. COMPARISON OF SLUG DATA WITH HOMOGENEOUS SYSTEM

figure. The horizontal asymptote for each curve is found to be 1.00. This is the theoretically expected value since, as the separation becomes large compared with the cross sectional area of the slugs, conditions approach those occurring in a dilute homogeneous solution. The value of the vertical asymptote is negative in each case which means that an array of a finite number of slugs in contact would go critical according to this particular method of extrapolation. In the experiments with the 400 slugs which were available a close packed array gave a multiplication of 3.3.

Having obtained the critical number of slugs for uniform square lattice spacing in single and double tiered arrays, it was necessary to estimate the minimum number of whole slugs which could be made critical in any water moderated, water reflected array. It was recognized that the influence of several factors had to be evaluated before a true minimum could be closely estimated. Some of the factors are:

1. The optimum separation between tiers

2. The relative lateral displacement of the two tiers

3. The effect of non-uniform slug spacing in the core

4. The effect of random stacking of the core

5. The moderating and reflecting efficiency of the plastic table and spacers used to support slugs

6. The thickness of water required for an effectively infinite reflector

Each of these factors is discussed briefly below:

1. Optimum separation between tiers. A series of experiments showed the reactivity of the system to be virtually insensitive to changes in the vertical separation of the two tiers up to about 0.50". Further increase in the spacing sharply decreased the reactivity.

2. Relative lateral displacement of the two tiers. For simplicity the majority of the two-tiered experiments was performed with the axes of the slugs in the two layers colinear. It was thought that slug columns arranged in this way might act as "neutron chimneys" permitting excess leakage from the core. Accordingly, an experiment was performed in which the top layer was laterally displaced in two dimensions by one-half the center-to-center distance between slugs. A small effect was found in the expected direction; the displacement lowered the critical mass of the optimum array by less than the equivalent of one slug.

3. The effect of non-uniform slug spacing in the core. The possibility that some non-uniform slug spacing might give a lower critical mass than precisely spaced uniform arrays was checked in two ways: (1) by making random shifts of approximately 1/8" in the positions of the slugs in the array; (2) by building three arrays containing the same number of slugs; one with uniform spacing, one with a denser center region and a third with a denser outer region. In all cases the arrays with uniform spacing had the highest activity.

4. The effect of random stacking of the core. A random arrangement of slugs will differ from a uniformly spaced one in two important respects: (1) the spacing will in general be non-uniform; (2) the array may have almost any shape. The first effect has already been discussed, the second requires further consideration. If an attempt be made to construct a core having optimum shape using whole slugs, the resulting non-uniform core spacing would be uninterpretable and might, for reasons discussed above, offset any expected gain in reactivity due to improved geometry. Accordingly, some of the standard 8" long P-10 slugs were cut into two and four inch lengths and used to improve the geometry without sacrificing uniform spacing. In this way it was possible, with a given mass of uranium, to achieve systems of higher reactivity than could occur in accidental stacking of whole slugs. Continued reduction of the size of the core units will tend, in the limit, towards a homogeneous core and will, therefore, yield safe though unrealistic specifications for slug processing. This possibility was minimized by stacking whole and partial slugs together in a uniformly spaced square lattice with all their axes vertical. By this means the critical number of slugs at optimum edge-to-edge spacing, 0.63", was reduced from 103 whole slugs in an essentially rectangular array 16" high to the equivalent of 99 whole slugs in one 14" high. On successive rearrangements of this array, the core was made thicker in the center and thinner at the edges, until its shape was roughly spherical. The core was then critical with the equivalent of 93 slugs. From a study of the intermediate critical assemblies it was judged that the array could not be improved by as much as one full slug by further changes in the shape. Allowing one slug for the lateral displacement effect noted above, the maximum number of P-10 enhanced alloy slugs which are safe in any water flooded array is set at 90. This result contains no significant safety factor.

5. The moderating and reflecting efficiency of the plastic. To provide a hydrogenous reflector below the core, it was assembled on the previously described plastic table and plastic spacers were used to keep the slugs in their proper position. A methacrylic plastic, such as Lucite and Plexiglass, had been selected as the material least likely to interfere with the critical conditions since both its moderating ratio and moderating power more closely approaches that of water than does any other readily available material.

Experiments were performed to confirm the expected behavior. The results obtained in thermal neutron systems, of some interest in themselves because of possible practical application, are included here.

In one set of experiments, a core of 104 slugs, with 0.63" edge-to-edge spacing, in two tiers was built on plastic pads of successively increasing thickness, up to approximately 9 inches, and then submerged in water. In this way the bottom of the core was completely reflected with plastic instead of water. The results, in Fig. 7, show no difference between the plastic and water within the limit of error.

Since, in typical assemblies, about 5% of the core volume was occupied by plastic, a second experiment was done in which 28.0% by volume of the water moderator was so replaced. As shown in Fig. 7 the change in reactivity was less than 0.25%. The results would not necessarily be applicable to other types of plastic, like the styrenes, which contain less hydrogen, or the vinylites, which contain chlorine.

6. The thickness of water required for an effectively infinite reflector. The thickness of water needed for an infinite water reflector can be estimated from the reciprocal multiplication curves of non-critical systems. The value obtained from these experiments is approximately 15 cm as shown by a typical plot in Fig. 8. The array cited was slab-like with high final multiplication, conditions which tend to emphasize the effect of additional water at large distances from the core. This dependence of the reactivity on the reflector thickness can be used as a sensitive indicator of extremely small changes in core reactivity, particularly when the reflector thickness is near infinite. The value of such a criterion, useful in measuring many of the effects discussed above, is illustrated by Fig. 7, in which it is shown that a relative change of less than 0.25% in the core mass is clearly observable.

Studies with Water Moderator and a Composite Lead and Water Reflector

Lead was compared with water as a reflector since the shielding properties of lead often demand it as a material of construction for handling and storage equipment. Specifically, tests were performed to determine the nuclear safety of a lead-lined shipping cask, described on drawing AEC-HOO-1001. The inside dimensions of the cavity in the specified cask were 15" x 10" x 9.2" and the maximum thickness of lead was 11". To insure conservatism in the results, the actual tests were performed in a slightly larger cavity of improved geometry, 14" x 14" x 10", and the thickness of the lead reflector was increased to at least 12". Not less than 8" of water reflector was provided outside the lead on all sides and the cavity was flooded.

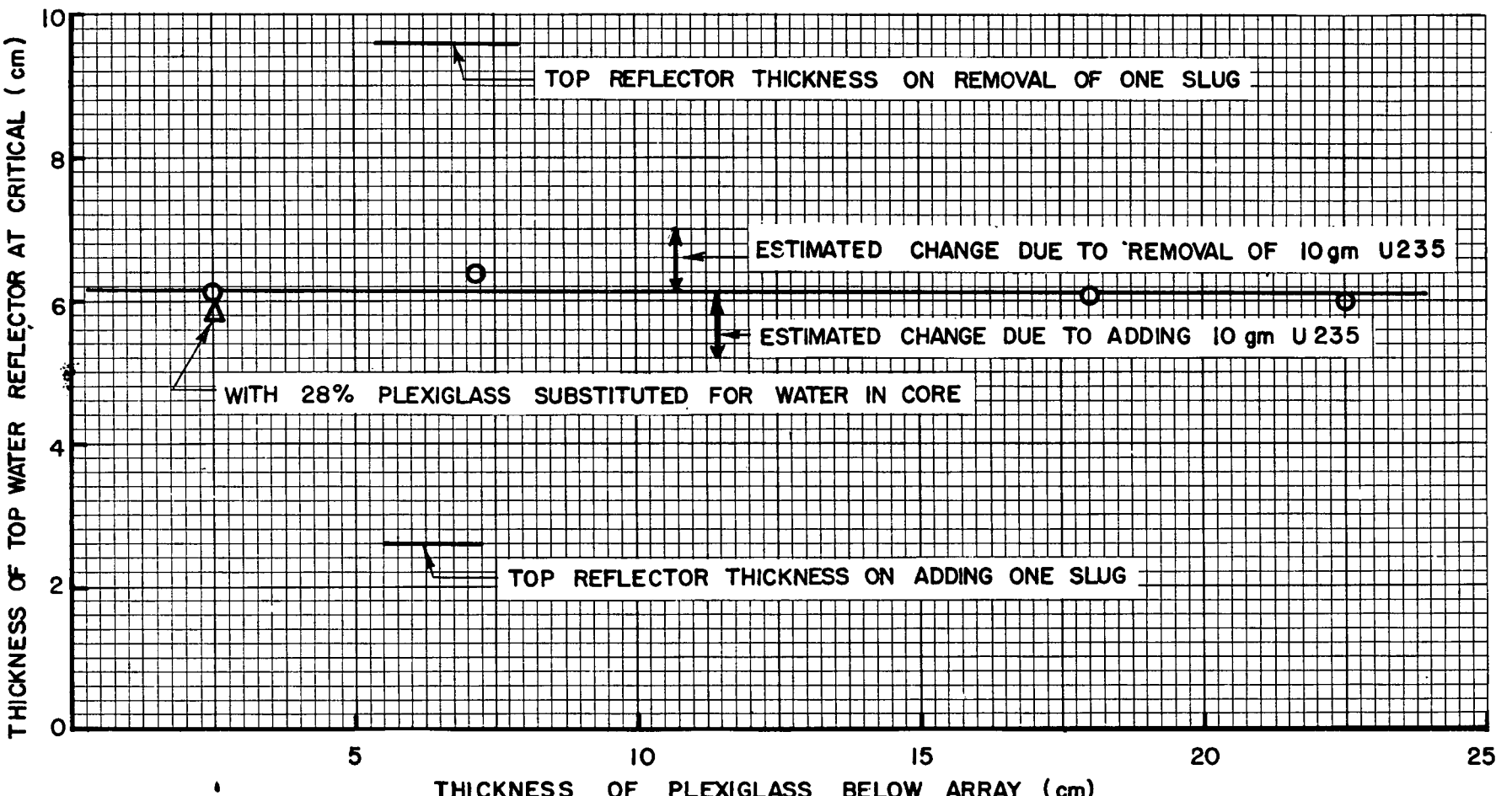

FIGURE 7. COMPARISON OF NUCLEAR PROPERTIES OF PLASTIC AND WATER CRITICAL ASSEMBLY OF 104 SLUGS

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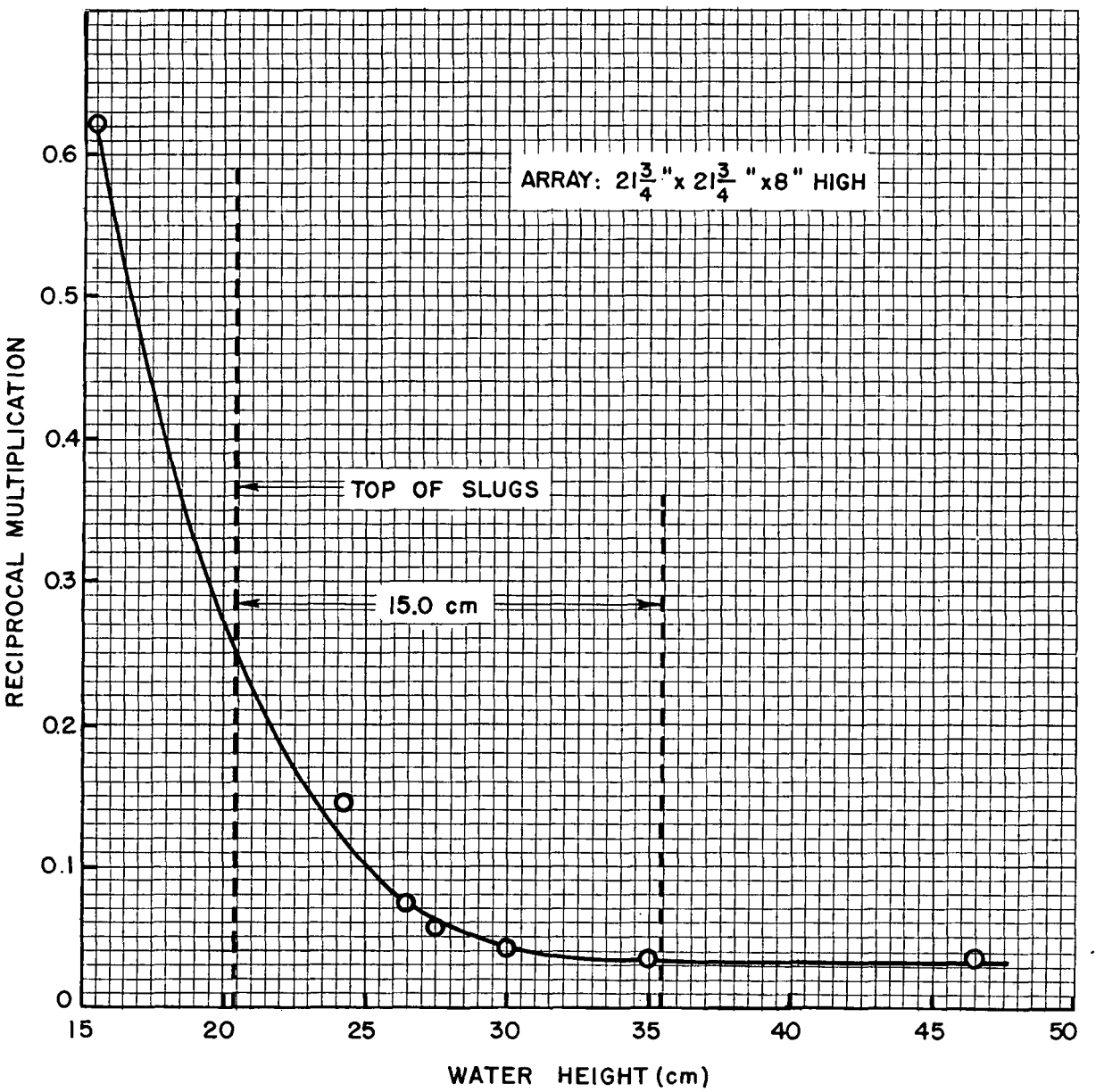

FIGURE 8. RECIPROCAL MULTIPLICATION vs WATER HEIGHT ABOVE BASE OF SLUGS

A series of experiments was performed in which from 36 to 100 slugs were placed in uniformly spaced arrays occupying the entire volume of the cavity. None of the arrays could be made critical. Fig. 9 shows the maximum neutron multiplication of each array as a function of the separation of the slugs. As can be seen, the maximum multiplication found was approximately 3.3 when 64 slugs were stacked with axes parallel in an 8 x 8 x 1 square array with 0.38" edge-to-edge spacing. Since each of the cask dimensions is greater than the length of one slug, random displacements of some slugs can occur in loading, giving the array an overall axial dimension greater than one slug length. The resulting activity of such an array could exceed that in which the ends of all slugs were coplanar; therefore, in some experiments alternate slugs were displaced 1 1/2" with respect to their immediate neighbors by Plexiglass spacers. The expected difference was detectable but insufficient to affect the final result as shown in Fig. 9. The results demonstrate that it is impossible to put a sufficient number of Hanford P-10 slugs into a completely inundated lead cask, drawing AEC-HOO-1001, to sustain a nuclear chain reaction. On the basis of prior experimental data the number of slugs which could be loaded per cask would have been limited to less than 29, equivalent to the critical mass of a homogeneous solution filling the carrier cavity.

Lead reflectors up to 12" thick were constructed of commercial lead brick both on the side and bottom of a slug array. In these experiments with lead, an infinite water reflector was present at all times. The following results were noted:

1. Lead is a better reflector than water under these conditions but the effect is small. In each of two well-moderated systems of good geometry the presence of a lead wall 4" thick along one of the six sides of the core and in contact with it lowered the critical mass by less than 1%. Assuming that for such small changes the effect is a linear function of the reflector area, the total reduction in critical mass would be 5 to 7% for a water moderated system totally enclosed in 4" of lead in contact with the core, and with an infinite water reflector outside the lead.

2. In no experiment was a measurable change in reactivity, i.e., one greater than 0.2%, found by increasing the thickness of the lead reflector beyond 4" or by increasing its area to one greater than that of the adjacent face of the core.

3. The effect of moving the reflector away from the core was also studied. The critical mass in a completely inundated system is insensitive to separation of core and lead reflector up to a separation of about 2". At 4" separation of core and lead, the critical mass was indistinguishable from that measured with a water reflector alone.

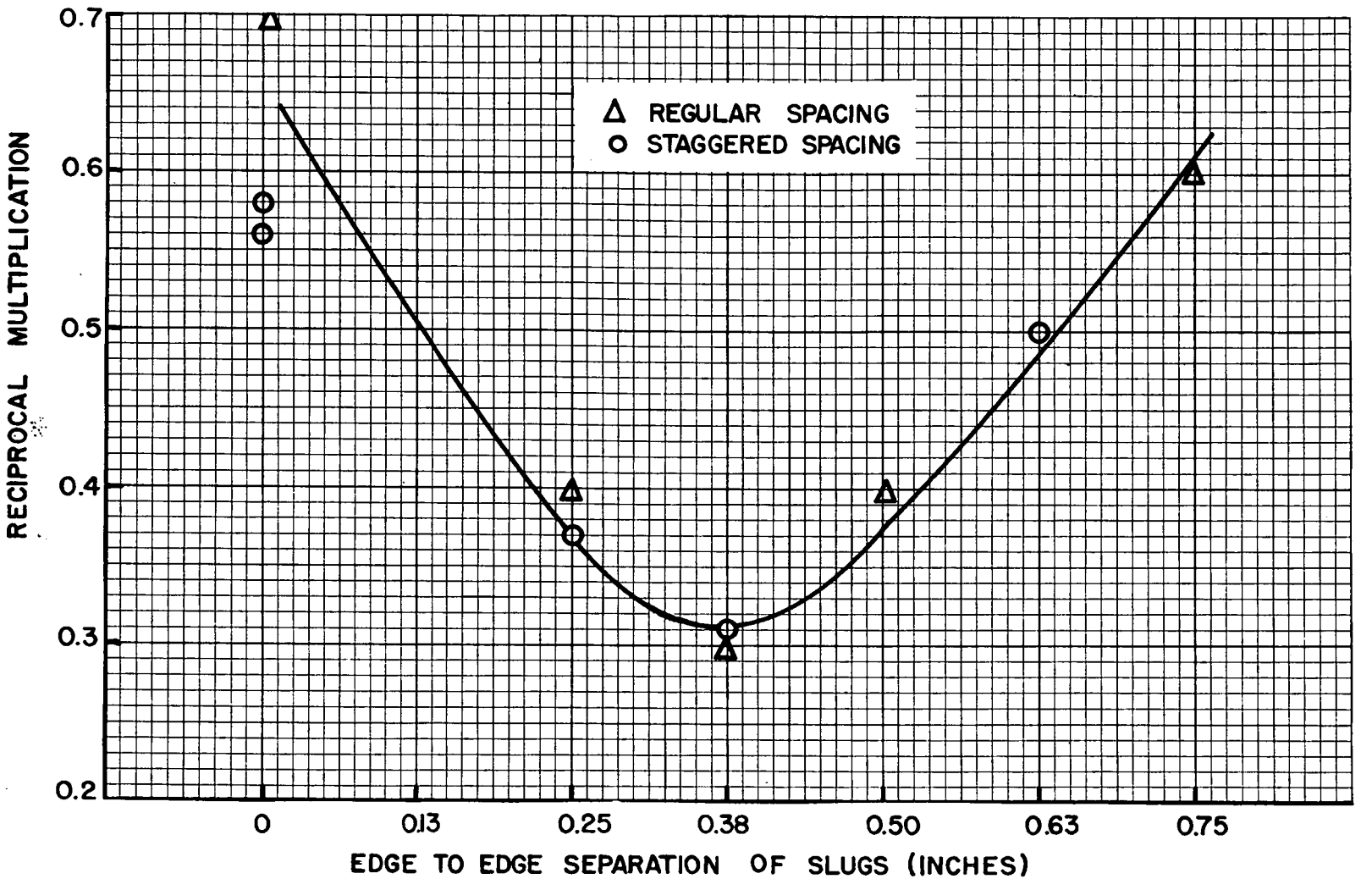

FIGURE 9. MINIMUM RECIPROCAL MULTIPLICATION
VS
SPACING OF SLUGS IN LEAD BOX

Studies with Water Moderator and a Composite Reflector of Natural Uranium Hanford Slugs and Water

The presence of natural uranium slugs in the water reflector reduced the number of enhanced slugs needed to produce a chain reaction by a factor of almost two. The experiments in this section are highly specialized due to the inflexible geometry of the P-10 and natural uranium slugs. Furthermore, experiments on natural uranium were, in the interest of economy, necessarily confined to conditions near optimum geometry and moderation. No claim is made that the sign of these effects would be the same under other conditions. Considerable caution should therefore be used in drawing any general conclusions from these results.

In initial experiments the natural uranium slugs were introduced into the core in two ways. When a natural slug was substituted for an enhanced one in the core lattice, it was found that the reactivity decreased in all cases, the decrease becoming smaller as the lattice position approached the core boundary.

Similarly, the insertion of natural slugs into a core having a full complement of enriched slugs displaced hydrogen and dearranged the uniform spacing of the enhanced slugs again lowering the activity considerably. As the natural slug was moved outward these effects became smaller until, at the edge of the core, they disappeared. Therefore, the experimental cores contained only alloy slugs. It is possible that, were the natural slugs of smaller diameter, they would reduce the number of enhanced slugs required for criticality.

The natural uranium, outside the enhanced core, is a good reflector, contributing to the neutron production. By a long series of trial and error measurements on selected arrays, the most effective spacing of the natural uranium slugs in the reflector was found to be that given below. Many of the experiments were done with the composite reflector on only one side of the core, it having been shown that the reflector savings was independent of the core face to which the reflector was adjacent. It is expected that the critical mass would be minimized by the following reflector:

1. The core enclosed in a nest of three box-like shells of close-packed natural uranium slugs, each one slug thick and separated from the adjacent shell by 1". The innermost shell 1" from the core.

2. The core and the space between the shells filled with water and an infinite water reflector provided beyond the outermost shell. A schematic of the array is shown in Fig. 10.

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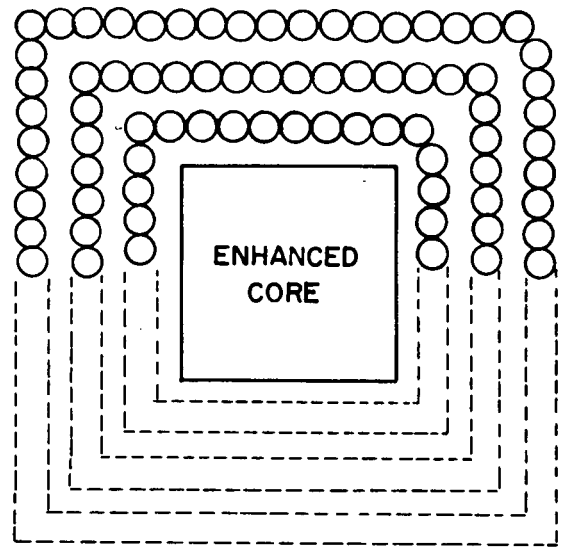

PLAN AT ELEVATION YY'

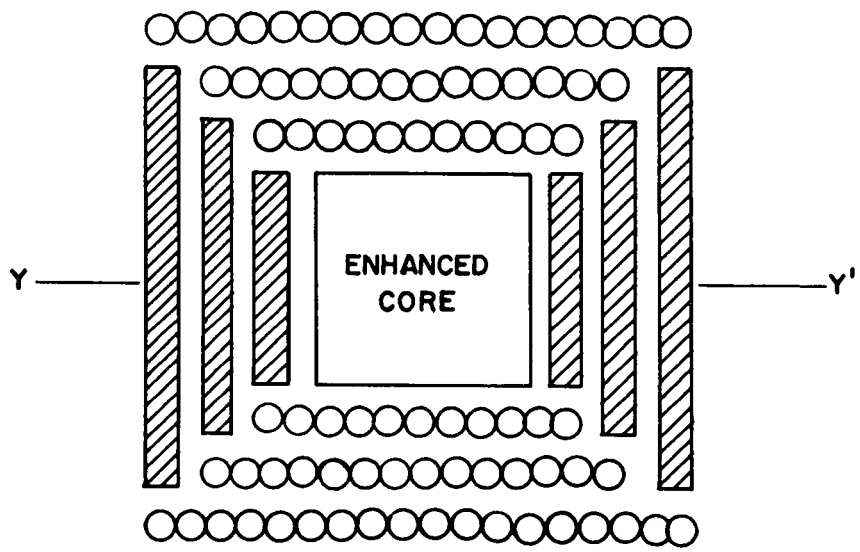

FIGURE 10. SCHEMATIC VIEW OF OPTIMUM CONSTRUCTION FOR REFLECTOR OF NATURAL URANIUM SLUGS AND WATER

The above reflector arrangement would be superior to ones in which:

1. Natural slugs were built into the core
2. The inner shell of natural uranium was in contact with the core
3. The spacing between successive shells differed from 1"
4. The shells were thicker than one natural slug
5. The natural slugs in any one shell were not close-packed
6. The reflector was a single box with walls of closely packed uranium slugs, from two to six rows thick, and flooded with water with an infinite water reflector outside the box.

It should be mentioned that the optimum position of the outermost shell could not be determined with accuracy due to its ineffectiveness and further addition of uranium did not measurably contribute to the reactivity. In contrast, the optimum positions of the first two shells were readily determined. The relative reflector value of the successive shells, on 1" spacing, was measured in a series of experiments in terms of the thickness of the top water reflector required for criticality. The results are given in Fig. 11. It can be seen that the third and fourth shells contribute relatively little.

The optimum spacing between core and reflector is best shown by a sequence of experiments in which an enhanced core was made successively critical with a single wall of natural uranium slugs at varying distances from one face of the core. The wall was six slugs thick in a close-packed hexagonal array, i.e., an interior slug had six nearest neighbors in contact with it. The results are given in Fig. 12, and show that the maximum reactivity occurs when the separation between core and natural uranium is about 1".

A core containing 54 whole enhanced slugs placed 5/8" edge-to-edge in a uniform two-tiered square array when completely enclosed in two shells of the natural uranium reflector shown in Fig. 10 became critical when completely flooded. By using partial slugs in the manner previously described, a similarly moderated and reflected core of dimensions 11 1/4" x 11 1/4" x 12" was critical using the equivalent of 51 slugs. The number of natural uranium slugs in the reflector was 649 or a ratio of natural to enhanced slugs of 108/9. A sketch of this array is shown in Fig. 13. The relative savings of successive layers of uranium reflector, as evaluated in the preceeding discussion, indicates that the number of P-10 slugs at criticality would not be greatly different from the value quoted here even in the presence of an infinite number of

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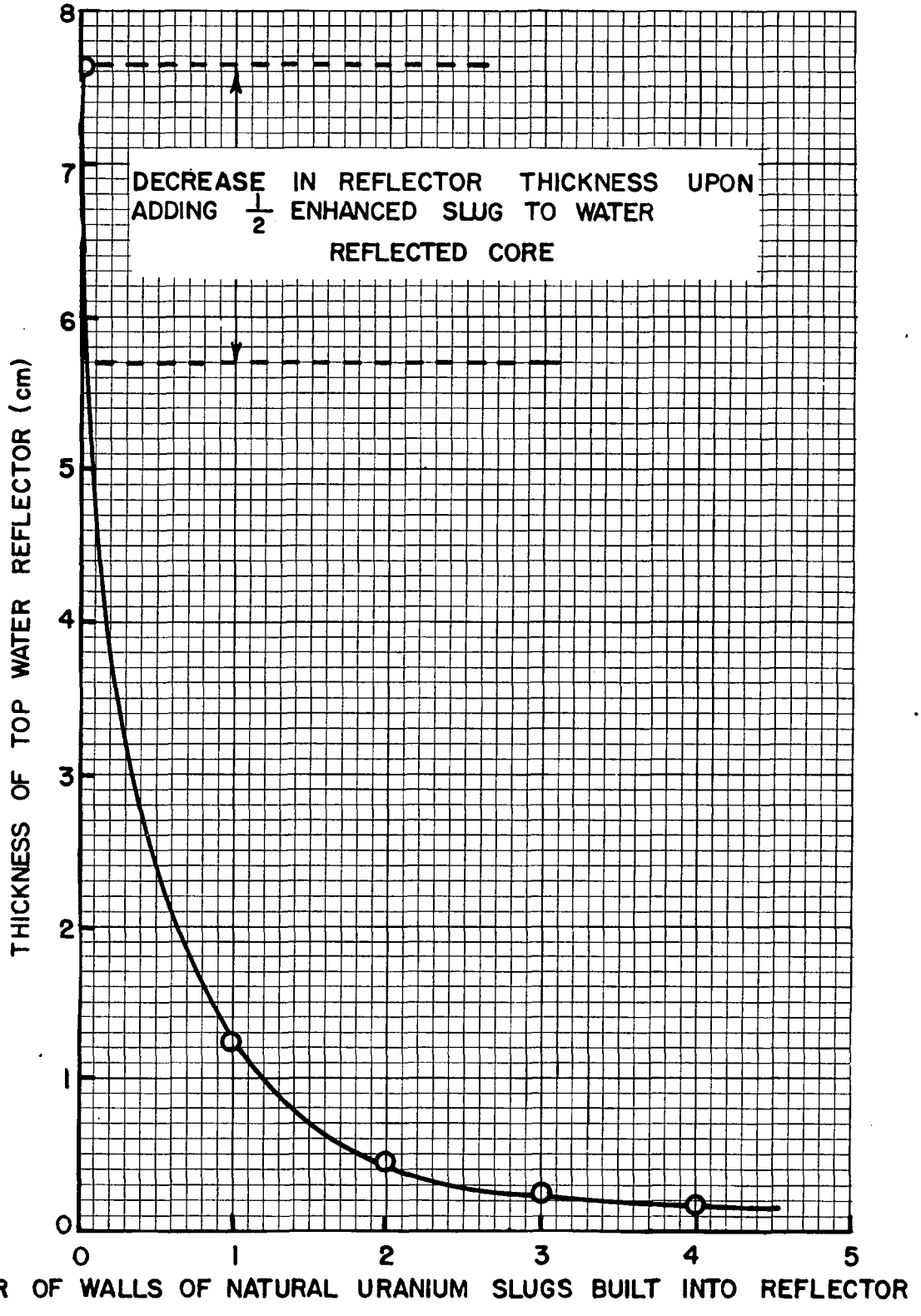

FIGURE II. CONTRIBUTION OF SUCCESSIVE WALLS OF NATURAL URANIUM TO THE REACTIVITY OF AN ENHANCED CORE

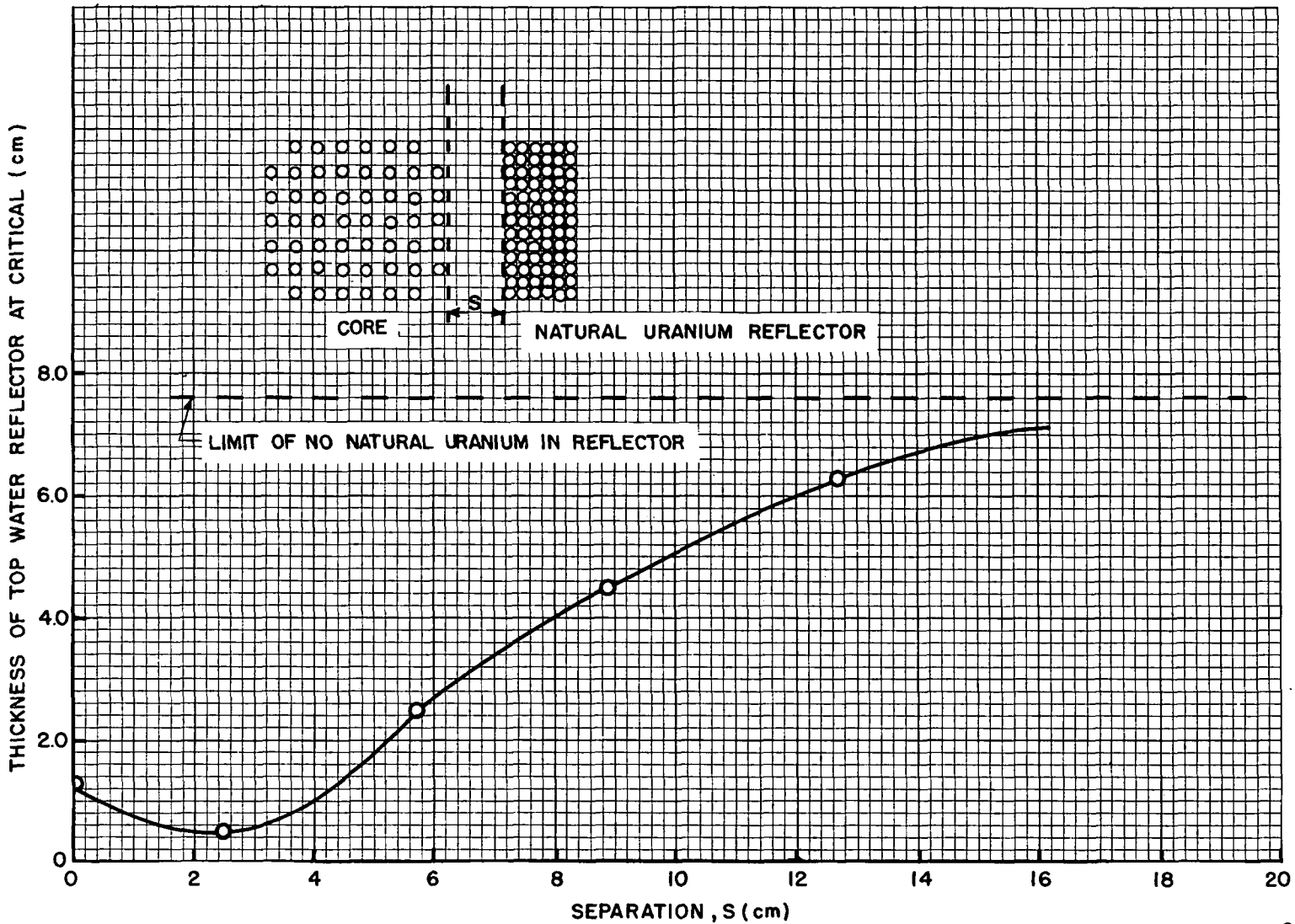

FIGURE 12. THICKNESS OF TOP WATER REFLECTOR AT CRITICAL
VS.
SEPARATION OF NATURAL URANIUM FROM CORE

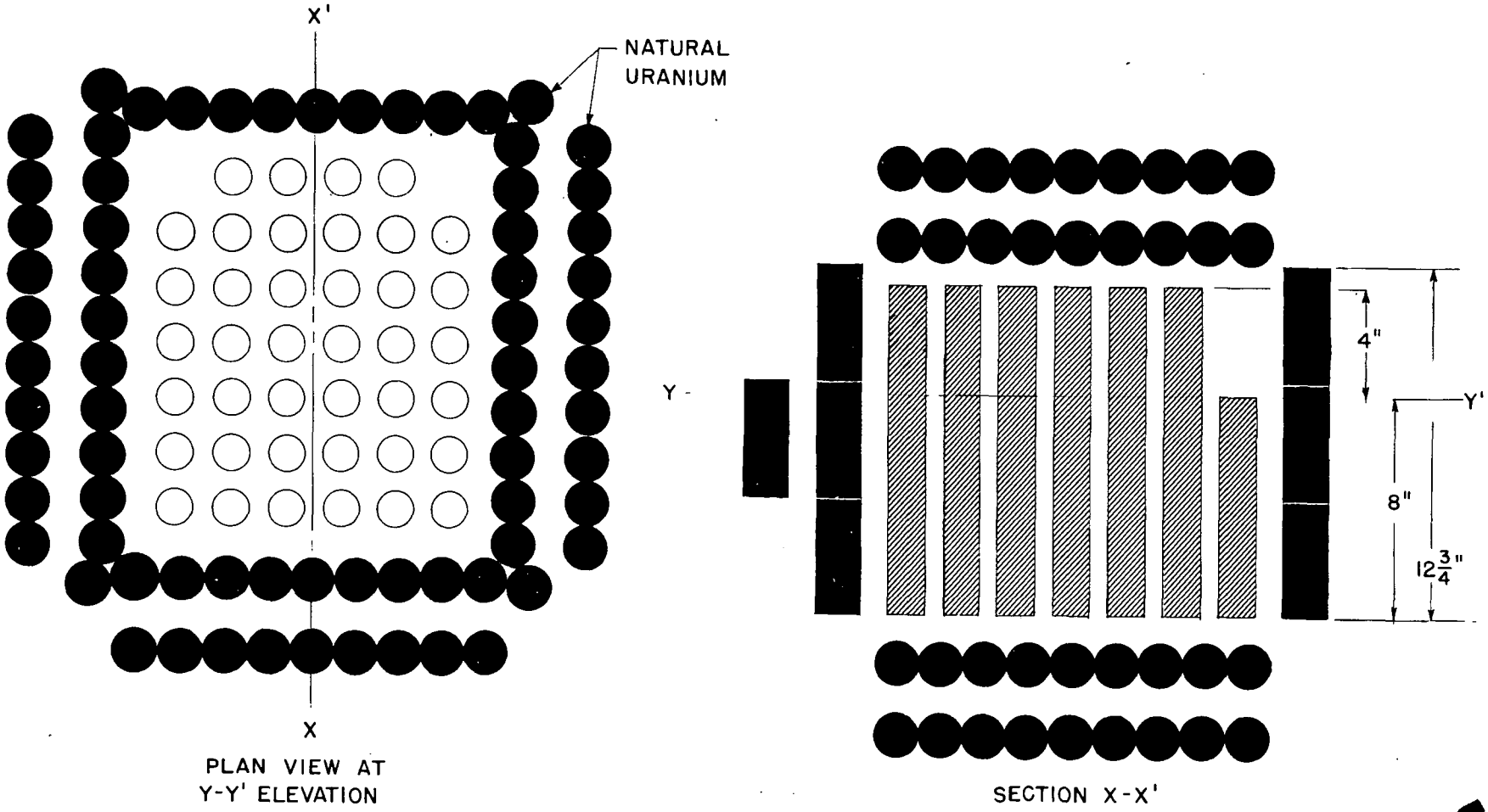

FIGURE 13. SLUG ARRAY FOR MINIMUM CRITICAL MASS WITH NATURAL URANIUM TO ENRICHED SLUG RATIO OF 38/9

natural slugs. The core shape approached a cube so closely that further changes in it would not alter the result sufficiently to justify the effort. Determining the optimum reflector position for cores with non-planar boundaries and the actual construction of such arrays would be prohibitively time-consuming. It was estimated that the improvements would not reduce the number of enhanced slugs required for criticality by more than three, thus reducing the estimated minimum number of enhanced slugs that could be made critical to 48. Accordingly, the maximum safe number is quoted as 47.

Interest was expressed in the minimum critical number of enhanced slugs when the ratio of natural slugs to enhanced slugs was 38/9, therefore, the natural uranium slugs in the previous array which were farthest from the core were removed and enhanced slugs were added until the array was again critical at the new 38/9 ratio. The number of P-10 slugs was then 59, an increase of eight. Applying the above corrections, the maximum safe number quoted becomes 55. The value contains no significant safety factor.

In conclusion, it is again pointed out that, for the most part, these are highly specialized experiments and would not be expected to apply to enhanced or natural slugs of other shapes, sizes, densities or uranium content. Generalization of the data should be approached with caution.

VII. ACKNOWLEDGEMENTS

The authors wish to acknowledge the able assistance of Mr. J. D. McLendon and Mr. P. E. Wilkinson in the performance of these experiments, of Mr. C. L. Schuske who assisted in the review of the data, and of Mr. W. H. Haase, Jr. who supplied the experimental group with health physics services during the program. Several helpful discussions were held with Dr. P. F. Gast and Mr. Frank Kruesi of Hanford during the course of the experiments.

VIII. APPENDIX

ESTIMATION OF THE CRITICAL MASS OF A HOMOGENEOUS CORE CORRESPONDING TO A GIVEN SLUG ARRAY

The aluminum associated with the U-235 in the alloy has three independent effects: it scatters the neutrons elastically, it absorbs a certain fraction of them, and it introduces a large amount of inhomogeneity into the core, all of which can be expected to affect the critical conditions. The calculation given here attempts to make some adjustment in the critical mass for the first two; the value so corrected is then compared directly with the experimental result to give some indication of the magnitude of the third.

The H:U-235 ratio of a critical homogeneous, unpoisoned water-reflected system with the same core dimensions as the slug array chosen for comparison is first determined from the dimensions of a right circular cylinder whose base has an area equal to that of the slug core, and whose height is equal to the slug core height. The procedure by which this is done by empirical methods is discussed elsewhere[3] and will not be repeated here.

The Al:U-235 atomic ratio of the P-10 alloy is 113:1. The number of hydrogen atoms having the same macroscopic thermal scattering cross-section as 113 atoms of aluminum is (113 x 1.35)/21 = 7.3. Thus, the scattering effect of the aluminum is to increase the initial moderation by seven. The implicit assumption is made that the mean energy loss per collision over the entire spectrum is the same for both water and aluminum.

The effect of the excess neutron absorption of the aluminum can now be taken into account using a method previously described.[4] The critical moderation, μ_3, for the poisoned system is

$$\mu_3 = \mu_2 - \frac{N_{Al}\,\sigma_{Al}}{N_{25}\,\sigma_{25}}\,\frac{\sigma_{25}}{\sigma_H}\,G = \mu_2 - 113\,\frac{0.22}{0.32} = \mu_2 - 78$$

Where N represents the number of atoms per cc.; σ, the absorption cross-section; G, the Greuling thermal leakage factor; $\mu_2 = \mu_1 + 7$, the critical moderation after correcting for the aluminum, and the subscripts 25, Al and H refer to U-235, aluminum and hydrogen, respectively.

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[4]Callihan, A. D., D. F. Cronin, J. K. Fox, J. W. Morfitt, "Critical Mass Studies, Part V," Carbide and Carbon Chemicals Company, K-25 Plant, K-643, June 30, 1950.

[redacted]

The Greuling factor G is set equal to one, its maximum value and that giving the best agreement with previous experiments.[4] Further refinements which might be made in the above formula are not justifiable. The final corrected moderation μ_3 is:

$$\mu_3 = \mu_1 + 7 - 78 = \mu_1 - 71$$

Thus the constant aluminum to uranium atomic ratio reduces the empirically determined H:U-235 ratios by a fixed amount. From the corrected H:U-235 ratio and the corresponding dimensions of the slug array, the critical mass of the corresponding homogeneous core can be calculated.

This method is applicable only when the empirically determined moderation is high, a condition which is met in these considerations.

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