EFFECTIVENESS OF LAMINATED LIQUID-SOLID RADIATION SHIELDING

by

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I. INTRODUCTION

A. Statement of Problem

An important factor in the design of shielding for mobile power reactors is weight. In stationary units where weight is not so important the shield is generally composed of separate layers of gamma-ray and neutron-shielding material. It has been suggested (1) that a homogeneous shield may have some advantages in increased shielding effectiveness and thereby give a saving in shield weight. It is only natural, therefore, to check this indication with aqueous solutions which could make a practical homogeneous shield, and to investigate the characteristics of this type of shielding.

The problem studied here consists of two parts. The first is the determination of the effect of varying homogeneity upon the shielding effectiveness of lead-cadmium sulfate solution and lead-boric acid shields. The second part is the determination of the change in the shielding effectiveness of these two shields as the concentration of the neutron absorber is varied in the solution.

B. Review of Literature

The literature survey disclosed little previous research into the effects on shielding properties of varying homogeneity or of varying the concentration of different shielding solutions. One exception, however, was Henson's (1) study of the effects of the degree of lamination on shielding effectiveness. While Henson's experimental set-up was somewhat different than that used here, it is feasible, keeping this in mind, to compare his general results with the present work. His data indicated an increase in shielding effectiveness with increased homogeneity and thus suggested the problem under consideration here.

II. MATERIALS AND APPARATUS

A. Source of Radiation

The gamma rays and neutrons used here were produced by a radium-beryllium source containing 94.7 milligrams of radium. The source was used in its original container consisting of a seven inch diameter lead ball enclosed in paraffin. With the top part of the paraffin and the lead plug removed a somewhat collimated source of gamma rays and fast neutrons and a plane source of slow neutrons was obtained.

While the exact spectrum of neutrons from this particular source is not known, it has been shown (2) for sources of this type that the maximum in the energy spectrum occurs at 5.5 Mev. and forms approximately a Gaussian distribution around this point. Thus the radiation from this source represents roughly that which is emitted from a nuclear reactor.

B. Shielding Materials

In each case the shielding materials used here were contained in a 20-gage sheet steel tank 9 by 11 by 16 inches and interposed between the source and detector. Therefore, the same volume of shield was used for each run.

The lead used was in the form of ten plates ½ by 8 by 16 inches, giving five inches of lead shielding and leaving six inches of solution shielding each time. Lead was chosen as an element of the shield because of its gamma shielding efficiency and was used in this form and amount because of ease of handling and the fact that five inches of lead reduces the gamma radiation to a safe but easily measurable level.

It is well known from microscopic cross section data that in general a material captures slow neutrons much more readily than fast ones. When it is necessary to shield against both fast and slow neutrons it is sometimes desirable to introduce a moderator as an element of the shield to thermalize the fast neutrons. The moderator chosen here was water because it has good moderating properties, is inexpensive, and will dissolve the necessary neutron absorbing compounds in fair amounts.

The neutron absorbing elements used here were boron and cadmium, which have high neutron capture cross sections and are readily available in water soluble compounds. Boron was used in the form H_3BO_3, boric acid crystals while the cadmium compound was $CdSO_4$, cadmium sulfate.

C. Detectors

An eight inch boron-10 lined tube was used for the neutron counts. This tube has been shown (1) to have reasonably complete discrimination between gamma rays and neutrons which is necessary for use in a mixed field. The tube and its accessory apparatus are shown in Figure 1 and a block diagram of the neutron counting circuit is shown in Figure 2.

In order to increase the probability that the neutrons counted had gone through the experimental tank and not been scattered into the detector by the walls of the room, a detector shield was used, as shown in cross section in Figure 3. It also facilitated satisfactory repositioning of the tube after removals.

The operating curve (Figure 4) was determined for the boron tube and indicates an operating voltage of around 630 volts. The tube was used at this voltage and the amplifier operated at full gain to increase the number of counts.

A Geiger-Müller tube with the standard scaling circuit was used to count gamma rays. The tube is approximately one inch in diameter and six inches long and was positioned back of the shield by means of a ring stand.

Figure 1. Apparatus

A -- Boron-10 Lined Tube

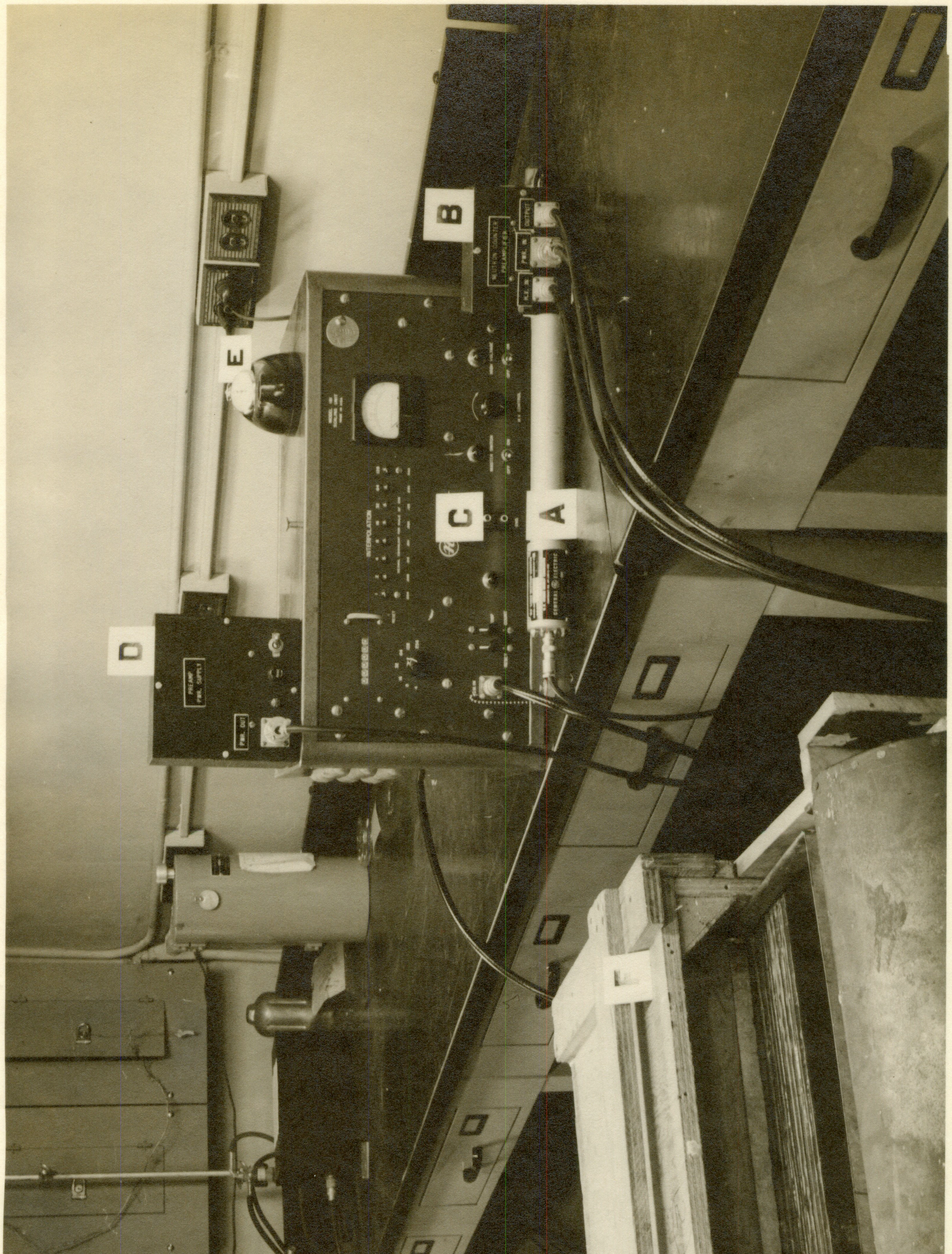
B -- Preamplifer

C -- Scaler

D -- Preamplifier Power Supply

E -- Stop Watch

F -- Source


A
B
C
D
E

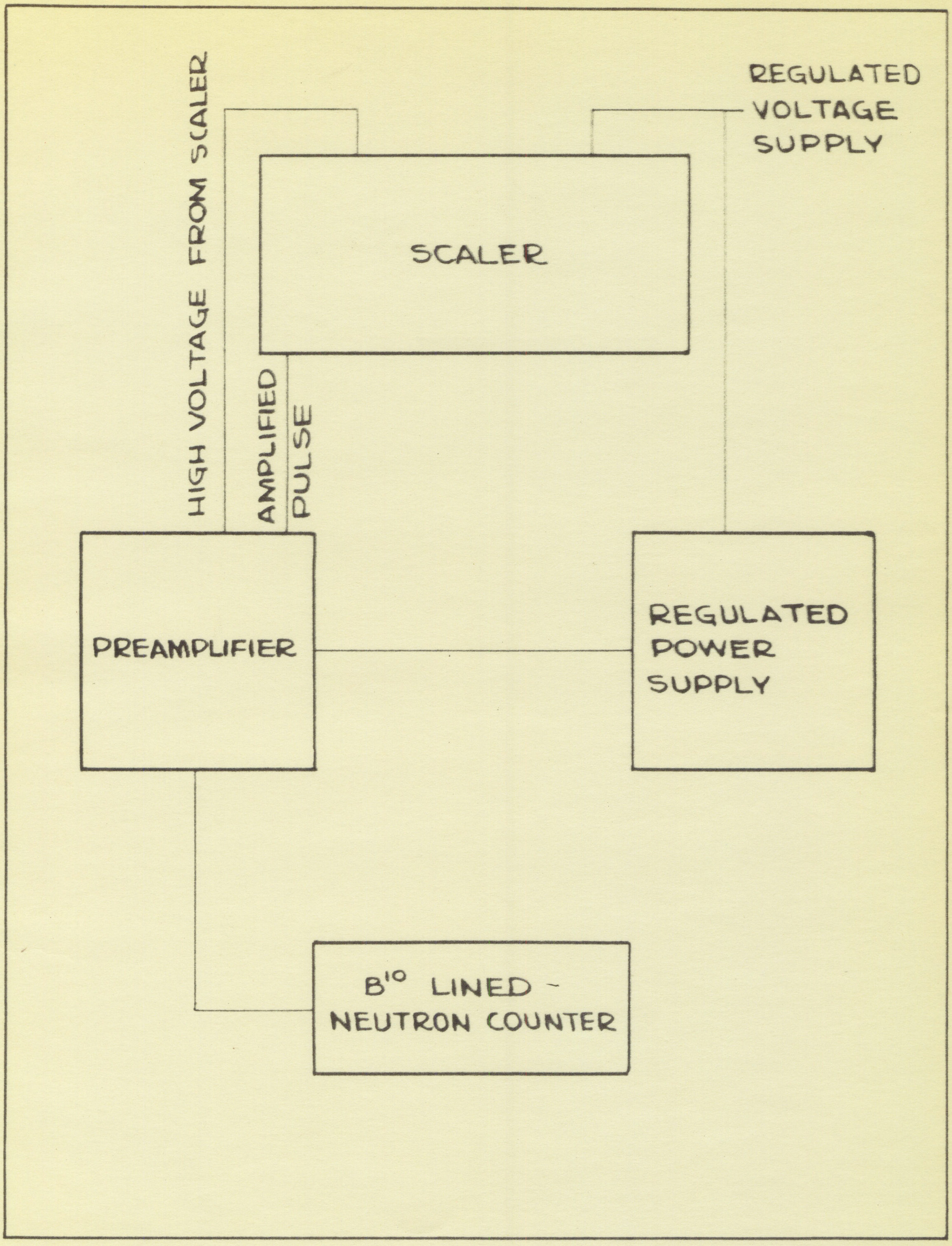


Figure 2. Neutron Counting Circuit -- Block Diagram.

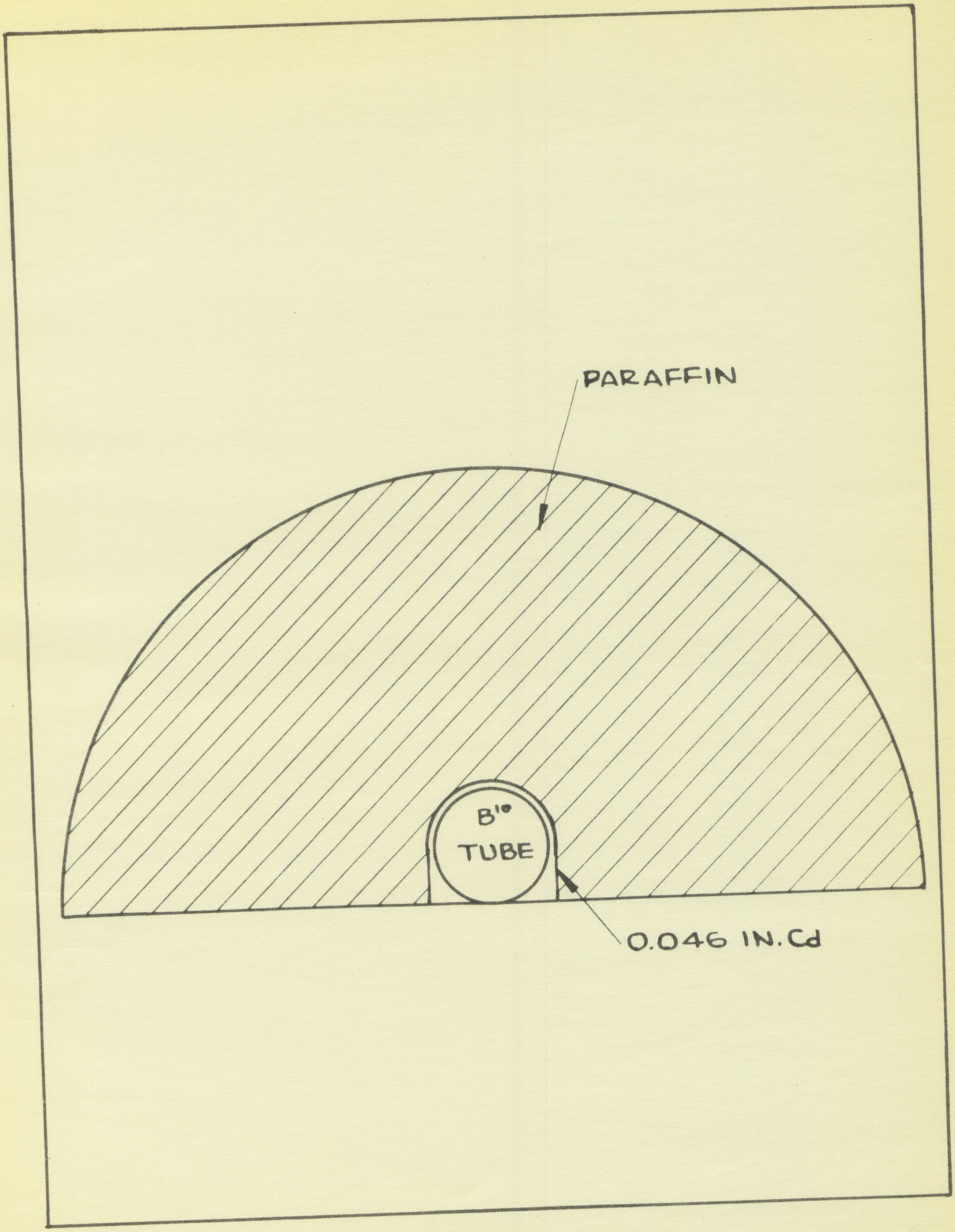


Figure 3. Detector Shield.

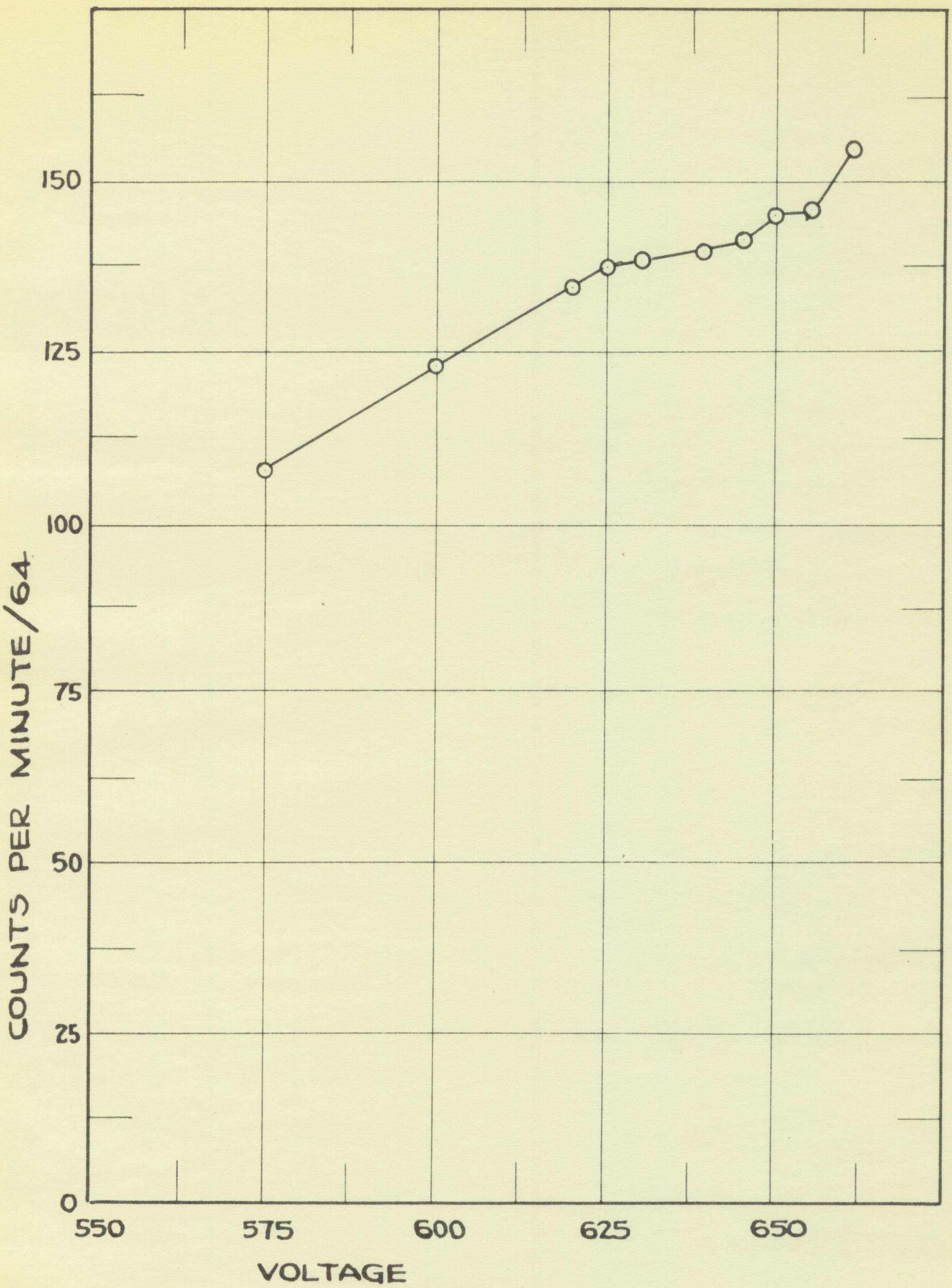


Figure 4. Operating Curve for B^{10} Lined Neutron Counter

III. PROCEDURE

A. General Considerations

The experimental arrangements used are shown schematically in Figure 5. The fast and slow neutron counts were separated by taking counts in each of the three positions shown. Since the boron tube will count neutrons of all energies to some extent, cadmium was used as shown in arrangement 2 to block off neutrons of energies less than 0.2 ev. by its high absorption resonance in that region. Thus the difference between readings under arrangements 1 and 2 is the slow neutron count where slow neutrons are defined here to have energies of 0.2 ev. and less. The 0.01 inch of cadmium was calculated to capture approximately 99 per cent of the incident slow neutrons. About three inches of paraffin were added between the cadmium and detector to obtain the fast neutron counts. The effect of this paraffin was merely to thermalize part of the fast neutrons in order to increase the counts and thereby reduce the effect of counts caused by neutrons reflected by walls into the detector. As can be seen by the different arrangements, the fast neutron counts were taken under a different geometry from

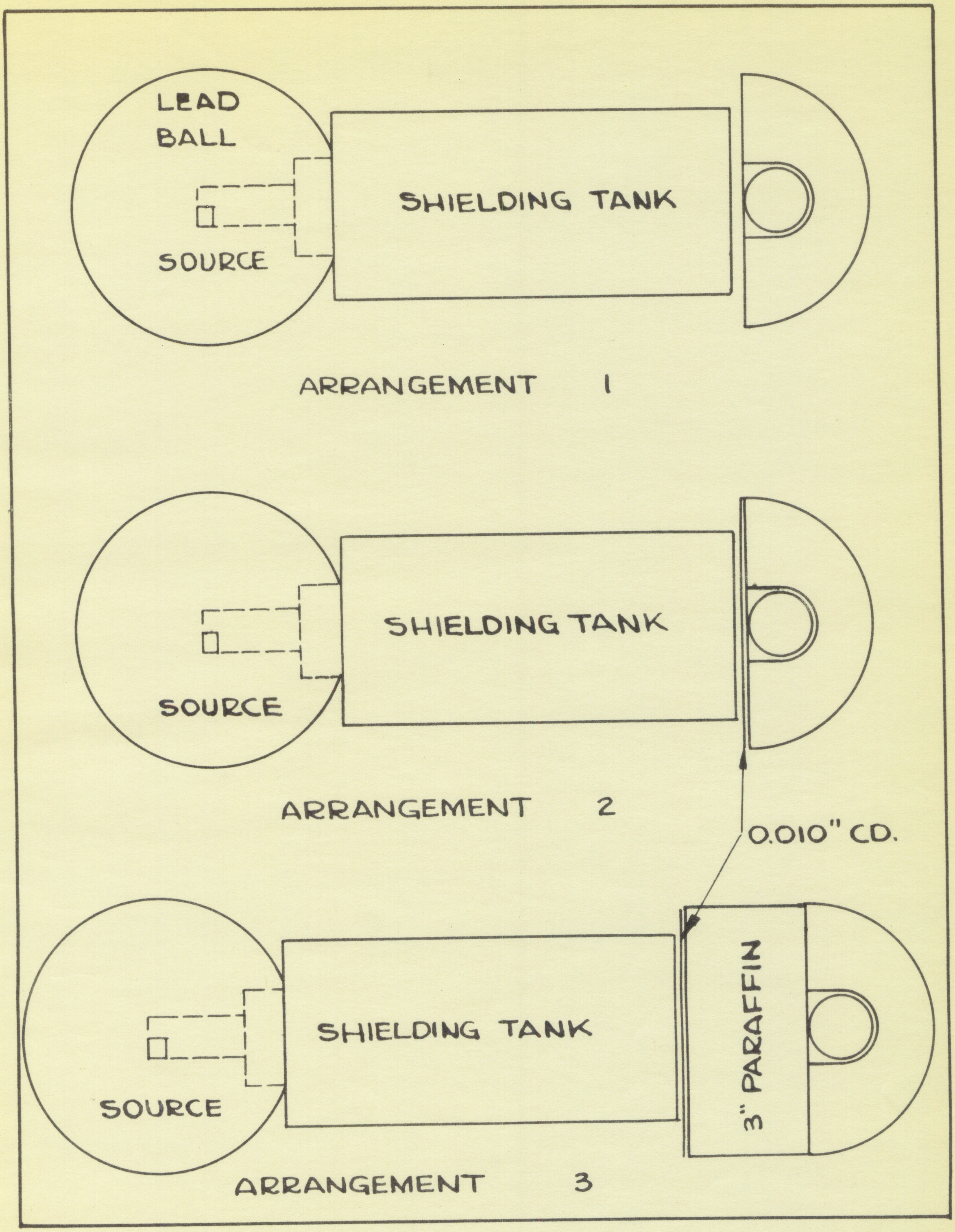


Figure 5. Experimental Arrangements for Neutron Counting.

the slow counts and this must be considered in any comparison of the fast and slow counts.

In order to reduce the effect of neutrons scattered into the shield through the sides, these four sides of the tank were wrapped in cadmium and paraffin. A sheet of cadmium 0.040 inches thick was placed adjacent to the tank and approximately two inches of paraffin were added next to this. Wrapping the shield in this manner tends to eliminate the stray neutrons which would be scattered through the edges of the shield and counted along with those which had traversed the entire thickness of the shield.

B. Effects of Lamination

A shielding cycle is defined here to be adjacent layers of equal thickness of lead and neutron absorbing solution. In the first case the lead portion of each cycle was positioned on the detector side of the solution layer of that particular cycle, and in the second case the lead in each cycle was placed on the source side of the solution. Thus by varying the cycles of shielding from one to ten, holding constant the total amount of material, a somewhat gradual approach was made toward a homogeneous shield. Readings were taken for one, two, five, and ten cycles or adjacent layers of 5, 2½, 1, and ½ inches thick. This was done for both the boric acid and the cadmium sulfate solutions in concentrations of 0.0416 gm/cc water and 0.087 gm/cc water respectively.

C. Effects of Concentration of Neutron Absorber in Solution

With the lead elements of the shield all adjacent to the source the amount of the neutron absorbing compound was varied in the solution making up the remainder of the shield.

For the boric acid an arbitrarily chosen unit concentration of 0.0416 gm/cc water was used. Readings were taken at this point and at 3/4, 1/2, and 1/4 of this concentration. A saturated solution of boric acid contains 0.048 gm/cc water so that the unit concentration used here was 86.8 per cent saturated.

The unit concentration of cadmium sulfate was taken as 0.087 gm/cc water or 7.25 per cent of the saturation value. Readings were taken at unit concentration and 3/4, 1/2, 1/4, and 1/8 of this amount. In each of these cases the saturation solubilities used were obtained from Seidell (3).

IV. RESULTS AND DISCUSSION

A. Effects of Lamination

1. Neutron shielding

The neutron counts taken under different degrees of lamination for each of the two solutions are listed in Tables 1 and 2. These counts were analyzed and separated into fast and slow neutron counts as shown in Table 3. Plots of these counts are made in Figures 6 and 7.

It can be seen that these curves in general indicate an increased shielding effectiveness with the increased degree of lamination. The shape of the curves for the boric acid solution, however, is quite dependent upon the statistics. It was therefore decided to check this run for both fast and slow neutrons in order to clarify the curves and also to check the reproducibility of the data. The results of this check are listed in Table 4 and plotted in Figure 8. While both Figures 6 and 8 show the general trend of decreasing counts with increased lamination, the vertical shift in the curves indicates, however, that exact reproduction of the set-up was not obtained.

Table 1

Neutron Counts for Boric Acid Solution

Arrangement	Cycles of Shielding Materials	Counting Time (Minutes)	Counts	Counting Rate (R) $R = \frac{\text{Counts} \pm \sqrt{\text{Counts}}}{\text{Time in Minutes}}$
1	1	20	8823	441 ± 4.7
1	2	15	6217	415 ± 5.3
1	5	16	5351	334 ± 4.5
1	10	15	5248	350 ± 4.8
2	1	73	13663	187 ± 1.6
2	2	33	5144	156 ± 2.2
2	5	38	5233	138 ± 1.9
2	10	37	5187	148 ± 1.9
3	1	105	36004	343 ± 1.8
3	2	20	6985	349 ± 4.2
3	5	65	18501	285 ± 2.1
3	10	15	4300	287 ± 4.3

Table 2

Neutron Counts for Cadmium Sulfate Solution

Arrangement	Cycles of Shielding Materials	Counting Time (Minutes)	Counts	Counting Rate (R) $R = \frac{\text{Counts} \pm \sqrt{\text{Counts}}}{\text{Time in Minutes}}$
1	1	20	5934	297 ± 3.9
1	2	24	6080	253 ± 3.2
1	5	21	5253	250 ± 3.4
1	10	22	5268	240 ± 3.3
2	1	32	6242	195 ± 2.4
2	2	75	11948	159 ± 1.5
2	5	42	6260	149 ± 1.9
2	10	51	7214	142 ± 1.7
3	1	14	5634	402 ± 5.4
3	2	20	6372	319 ± 3.9
3	5	18	5353	297 ± 4.0
3	10	18	5172	288 ± 3.9

Table 3

Slow and Fast Neutron Counts

Solution	Cycles of Shielding Materials	Slow Neutron Counting Rate $(R_1 - R_2 \pm \sqrt{\sigma_1 + \sigma_2})$*	Fast Neutron Counting Rate
Boric Acid	1	254 ± 5.0	343 ± 1.8
	2	259 ± 5.7	349 ± 4.2
	5	196 ± 4.9	285 ± 2.1
	10	202 ± 5.2	287 ± 4.3
Cadmium Sulfate	1	102 ± 4.6	402 ± 5.4
	2	94 ± 3.6	319 ± 3.9
	5	101 ± 3.9	297 ± 4.0
	10	98 ± 3.7	288 ± 3.9

*Subscripts refer to arrangement in Figure 5.

Table 4

Check on Neutron Counts for Boric Acid Solution

Cycles of Shielding Materials	Slow Neutron Counting Rate $(R_1 - R_2 \pm \sqrt{\sigma_1 + \sigma_2})$	Fast Neutron Counting Rate
1	265 ± 7.0	406 ± 5.4
2	260 ± 6.9	408 ± 5.6
5	221 ± 5.9	314 ± 4.2
10	222 ± 5.9	317 ± 4.4

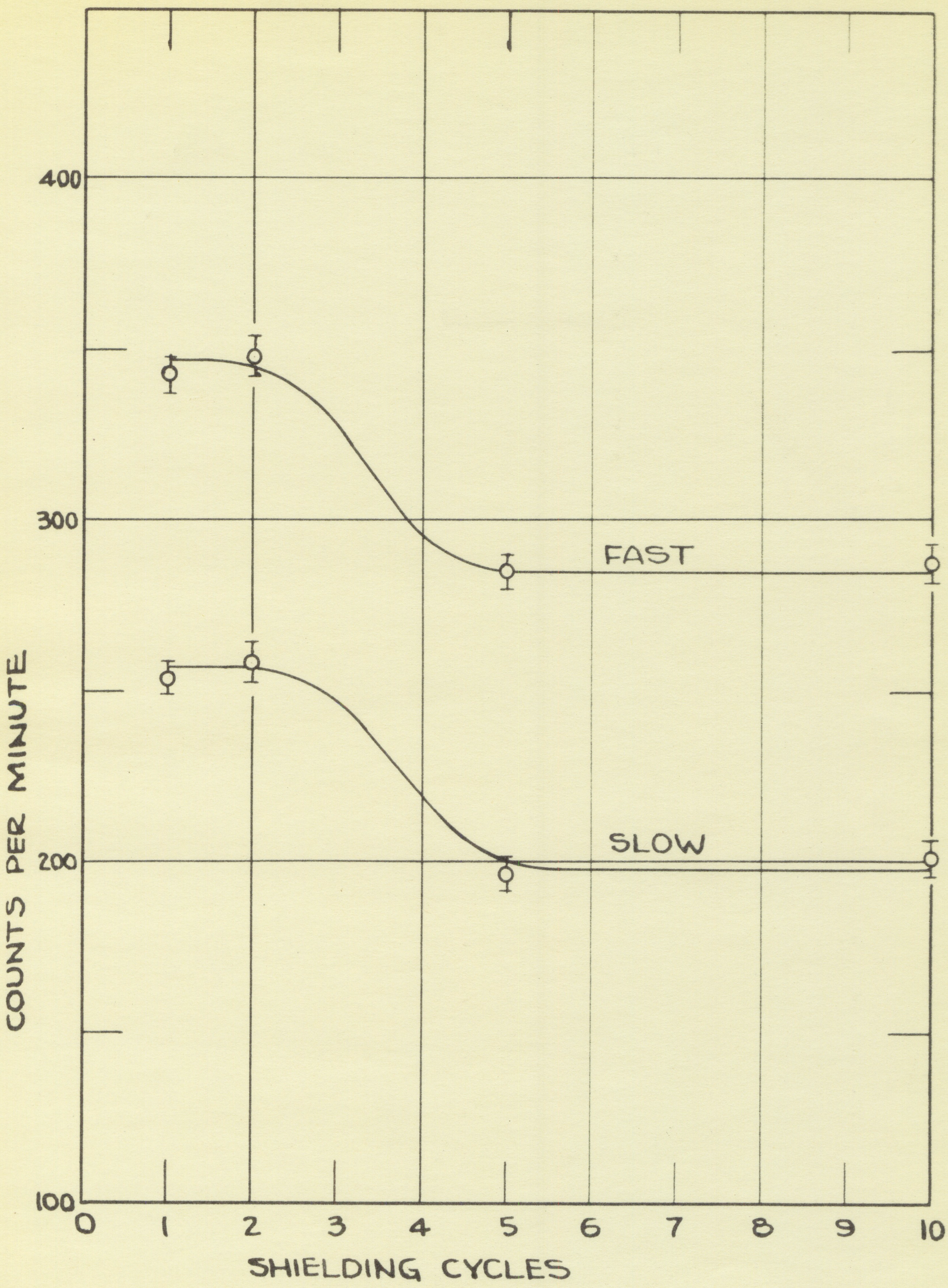


Figure 6. Neutron Counts for Boric Acid Solution.

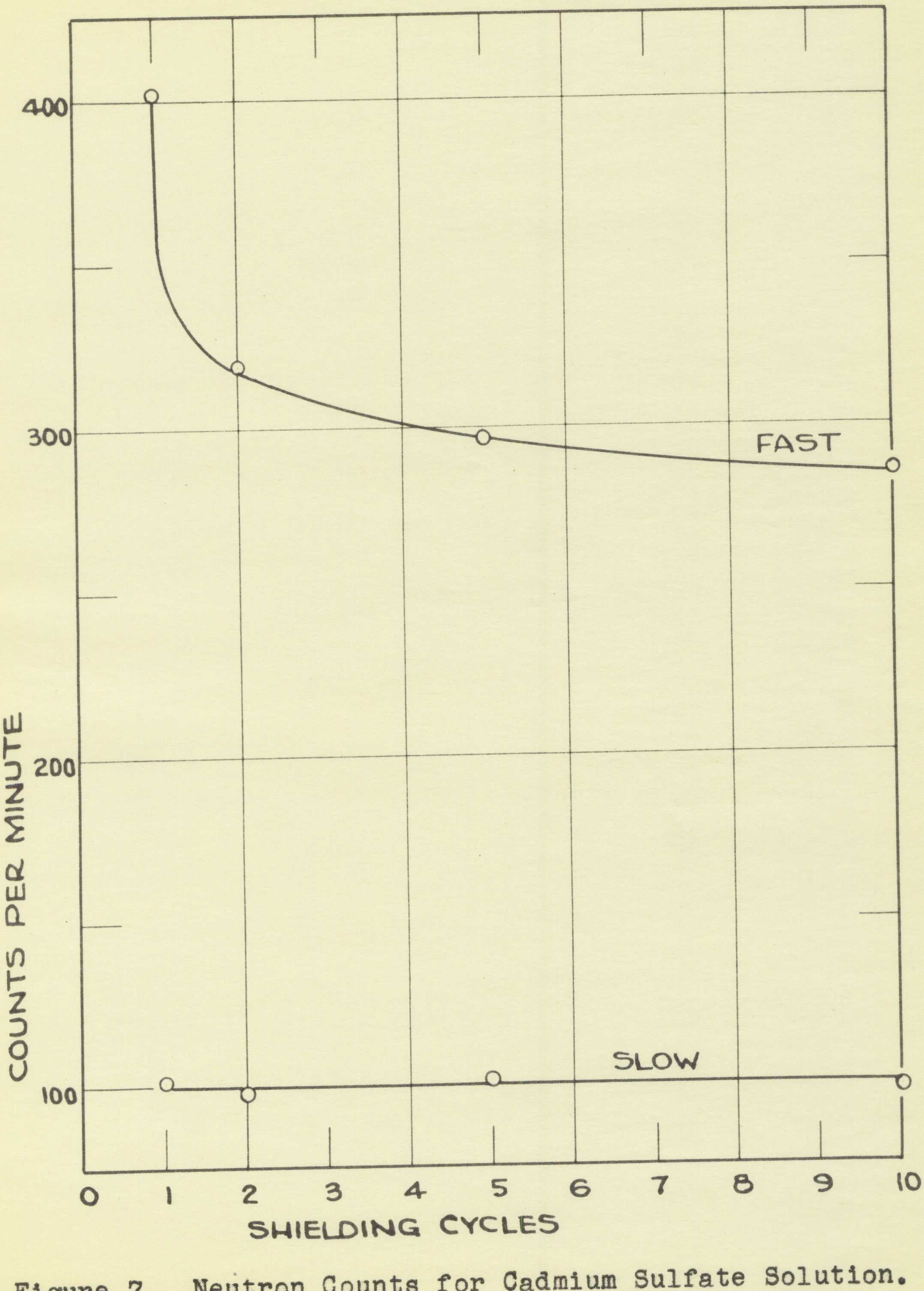


Figure 7. Neutron Counts for Cadmium Sulfate Solution.

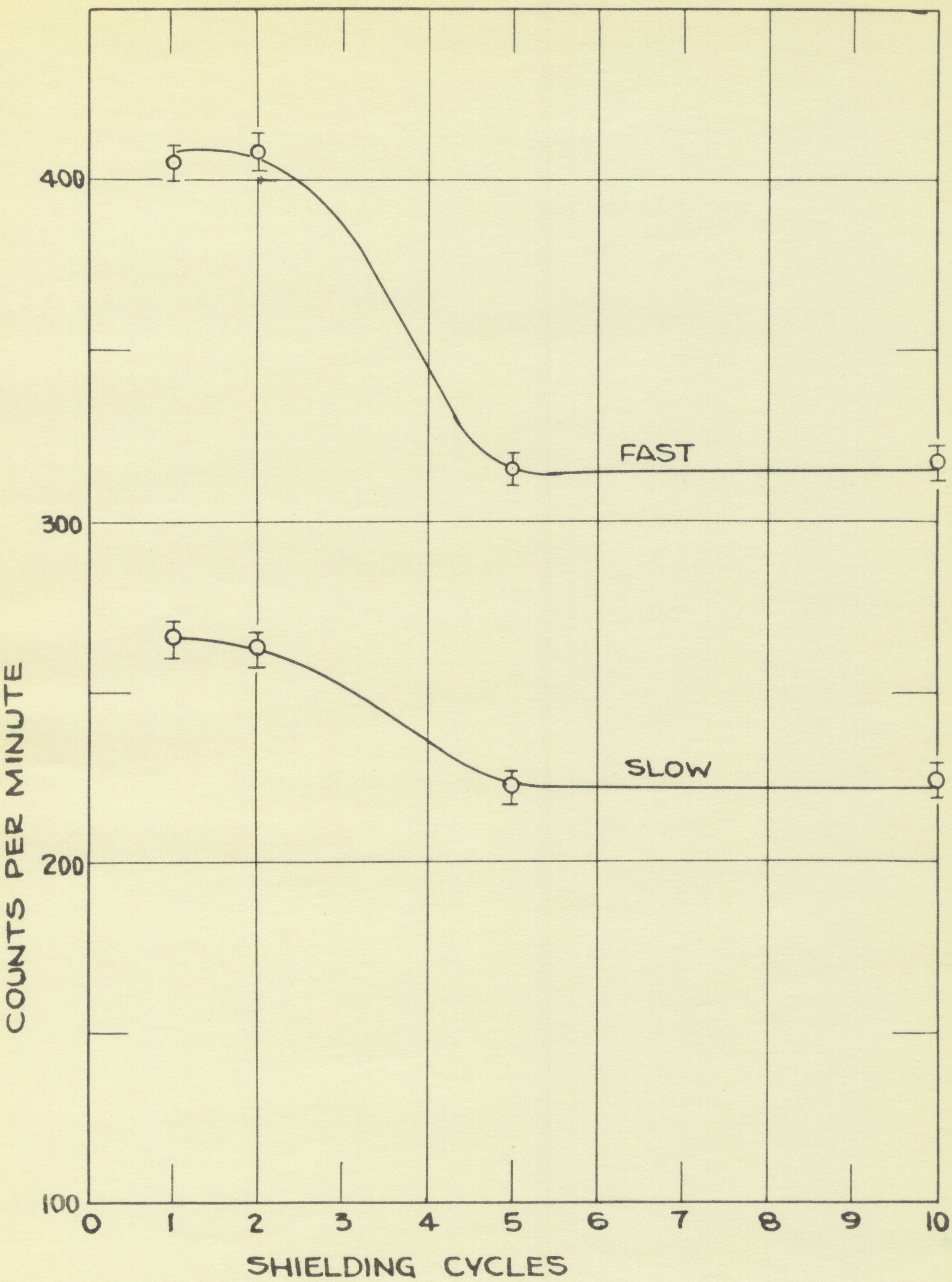


Figure 8. Check on Neutron Counts for Boric Acid Solution.

It is believed that the increased neutron shielding effectiveness as lamination increases may be attributed to (1) a more efficient positioning of the lead and (2) a change in the probability that neutrons will enter the solution and that those leaving the solution will be counted. The latter may be brought about by moving the moderator - absorber farther away from the source. Further research was conducted to help clarify this point. Readings were taken as the degree of lamination was changed under starting conditions A and B shown in Figure 9. These neutron counts are tabulated in Table 5 and plotted in Figure 10.

In order to appreciate more fully these data a further study should be made of possibilities (1) and (2) given in the preceeding paragraph. Cross section data indicate that the moderation effect of lead on neutrons is small but measurable. One can see that, starting from position A, as more and more lead is interposed between the solution and the source it will moderate more and more neutrons into the higher capture cross section region of the solution; thus giving a lower count as the number of laminations is increased. Another possible cause for the decrease in counts may be of a geometrical origin. Starting from position A and increasing the number of laminations, the effect is to move the solution

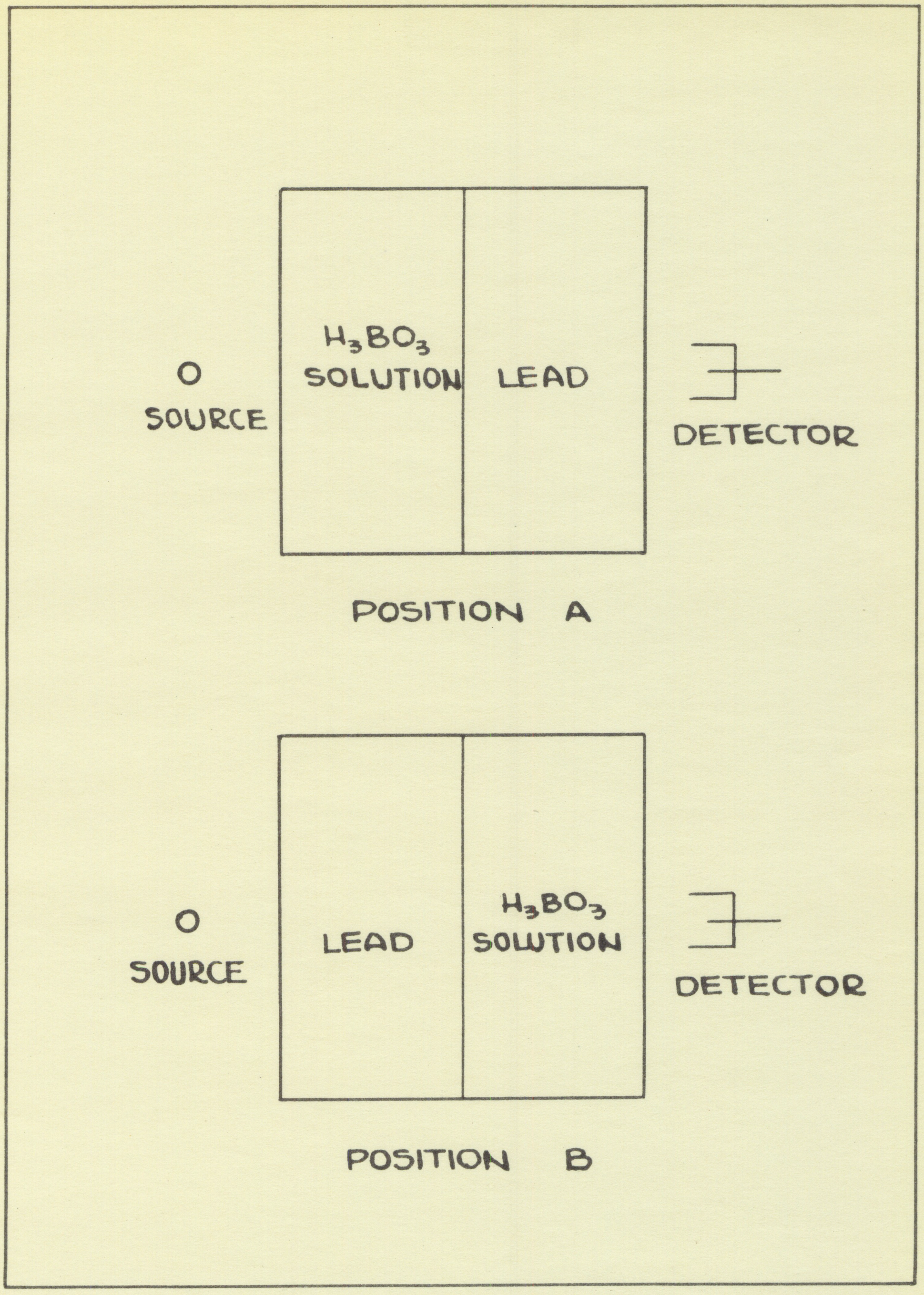


Figure 9. Basic One Cycle Configurations.

progressively away from the source and the lead toward the source. This increases the distance between the source and the effective entrance face of the solution, which of course alters the probability of neutrons from the source entering this face of the solution. On the detector side a change is also made in the probability that neutrons which leave the exit face of the solution will reach the detector. In order to see if the changes of these two probabilities balance as the degree of lamination is changed, data were taken starting from position B. The resultant increase in counts with increased lamination and the relative position of the end points of the curves in Figure 10 show that this geometrical effect is important. Since the effect of more efficient positioning of the lead is very small, the product of the entrance and exit probabilities mentioned previously must decrease as the moderator is effectively moved away from the source.

2. Gamma shielding

The gamma counts for the different degrees of lamination are listed in Table 6 and plotted in Figure 11. The curves indicated a general increase in gamma shielding effectiveness with increased lamination which can be explained by an analysis of the interaction of gamma rays with matter.

Table 5

Neutron and Gamma Counts for Boric Acid Solution

Cycles of Shielding Materials		Slow Neutron Counting Rate	Fast Neutron Counting Rate	Gamma Counting Rate
A	1	275 ± 5.9	397 ± 5.4	1208 ± 10.8
	2	271 ± 5.9	390 ± 5.6	1099 ± 10.4
	5	237 ± 6.1	316 ± 4.8	1040 ± 10.1
	10	229 ± 6.3	313 ± 4.2	1006 ± 10.1
B	1	191 ± 5.8	207 ± 5.6	952 ± 9.8
	2	195 ± 5.7	212 ± 5.9	1000 ± 10.2
	5	217 ± 6.0	277 ± 5.6	1040 ± 10.1
	10	222 ± 6.1	283 ± 5.8	1059 ± 10.1

Table 6

Gamma Counts

Solution	Cycles of Shielding Materials	Counting Time (Minutes)	Counts	Counting Rate $\frac{\text{Counts}}{\text{Time in Minutes}}$
Boric Acid	1	10	12211	1221 ± 11.0
	2	11	12158	1105 ± 10.0
	5	11	11325	1030 ± 9.7
	10	10	10128	1013 ± 10.0
Cadmium Sulfate	1	9	10480	1164 ± 11.4
	2	11	12052	1095 ± 10.0
	5	11	11458	1043 ± 9.7
	10	10	10512	1051 ± 10.2

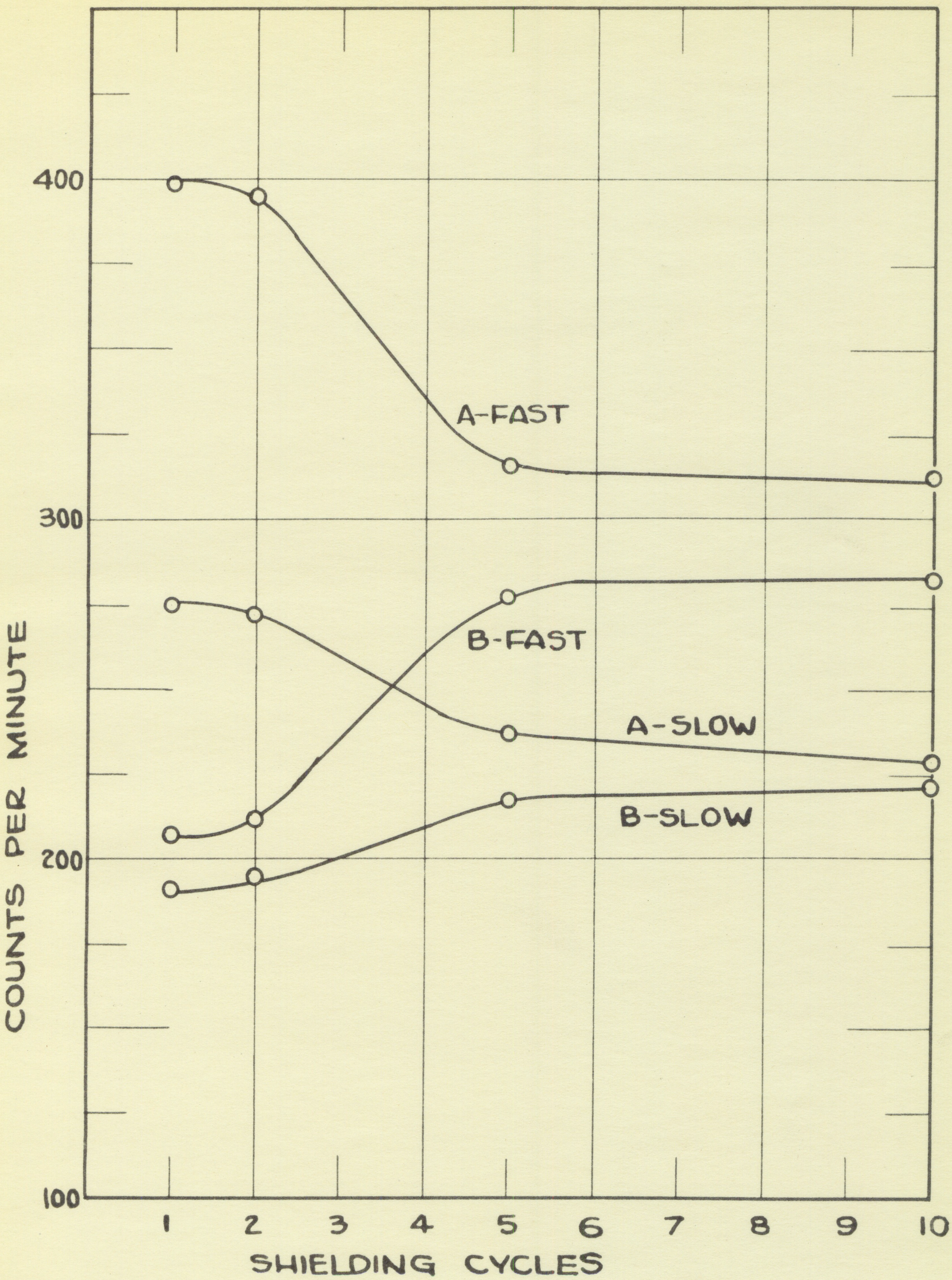


Figure 10. Neutron Counts.

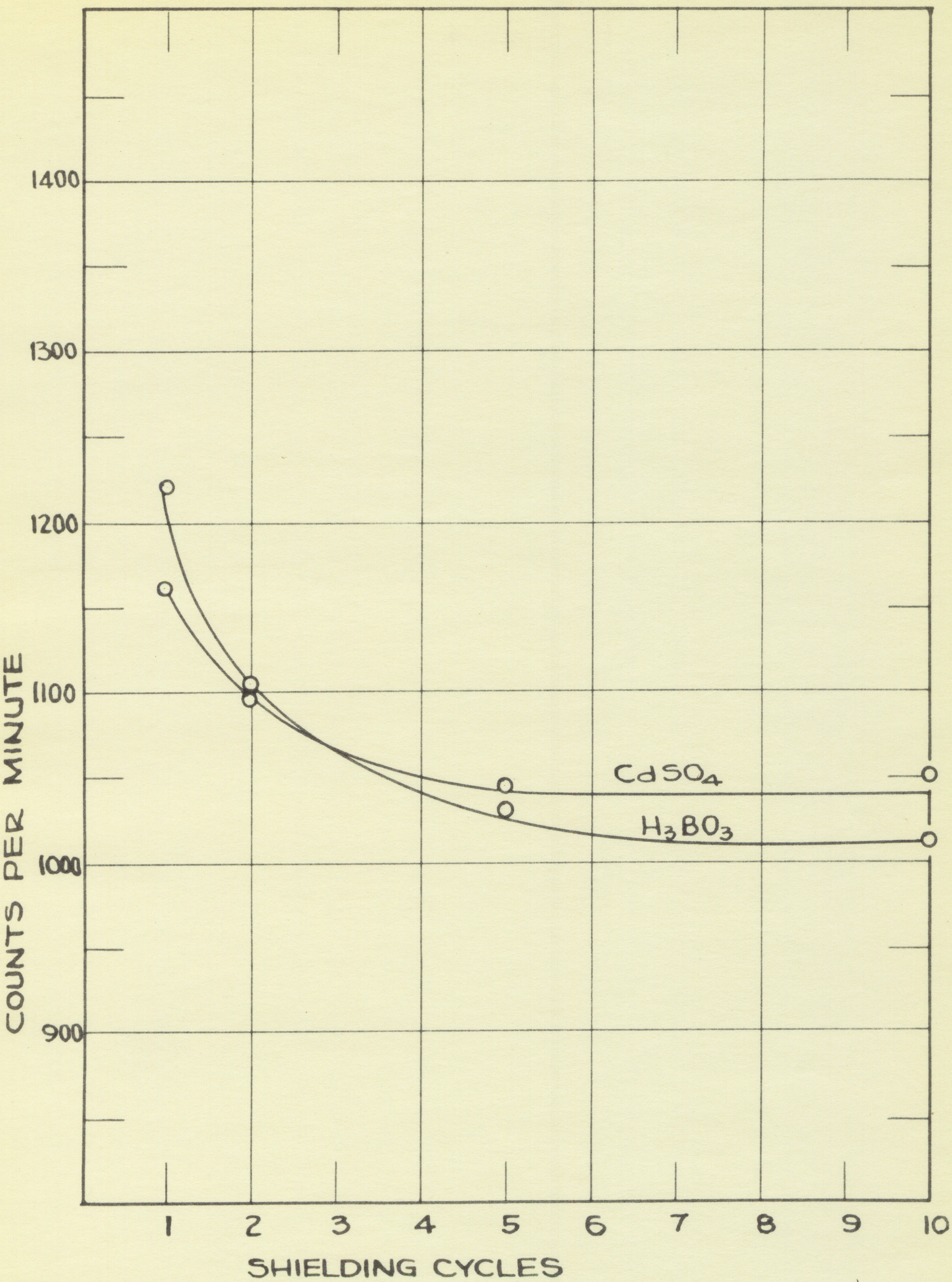


Figure 11. Gamma Counts.

It has been shown (4) for light elements that there is a definite increase in the mass absorption coefficient as the gamma ray energy drops below 0.1 Mev. Lighter elements and compounds have little effect on gamma rays of high energy. In the one cycle configuration the solution has only a slight effect on the relatively high energy gammas emitted by the radium. With the higher degrees of lamination, however, the gamma rays are slowed down by Compton scattering with the lead into the energy range where the solution has a measurable absorption effect.

A geometrical analysis similiar to the one in the preceeding sector indicates, however, that this more efficient positioning of the solution is not the only cause. Data were taken for gamma rays starting under conditions of position B. These are tabulated in Table 5 and plotted in Figure 12. The general shape of the curves and the fact that they overlap indicate that there is more efficient positioning of the solution and that the geometrical effect is important also.

It must be remembered in the gamma ray analysis that the lead is the important element in the shield. Curve A, by its negative slope indicates that the dominant effect here is that of more efficient positioning of the solution. This is true since moving the lead toward the

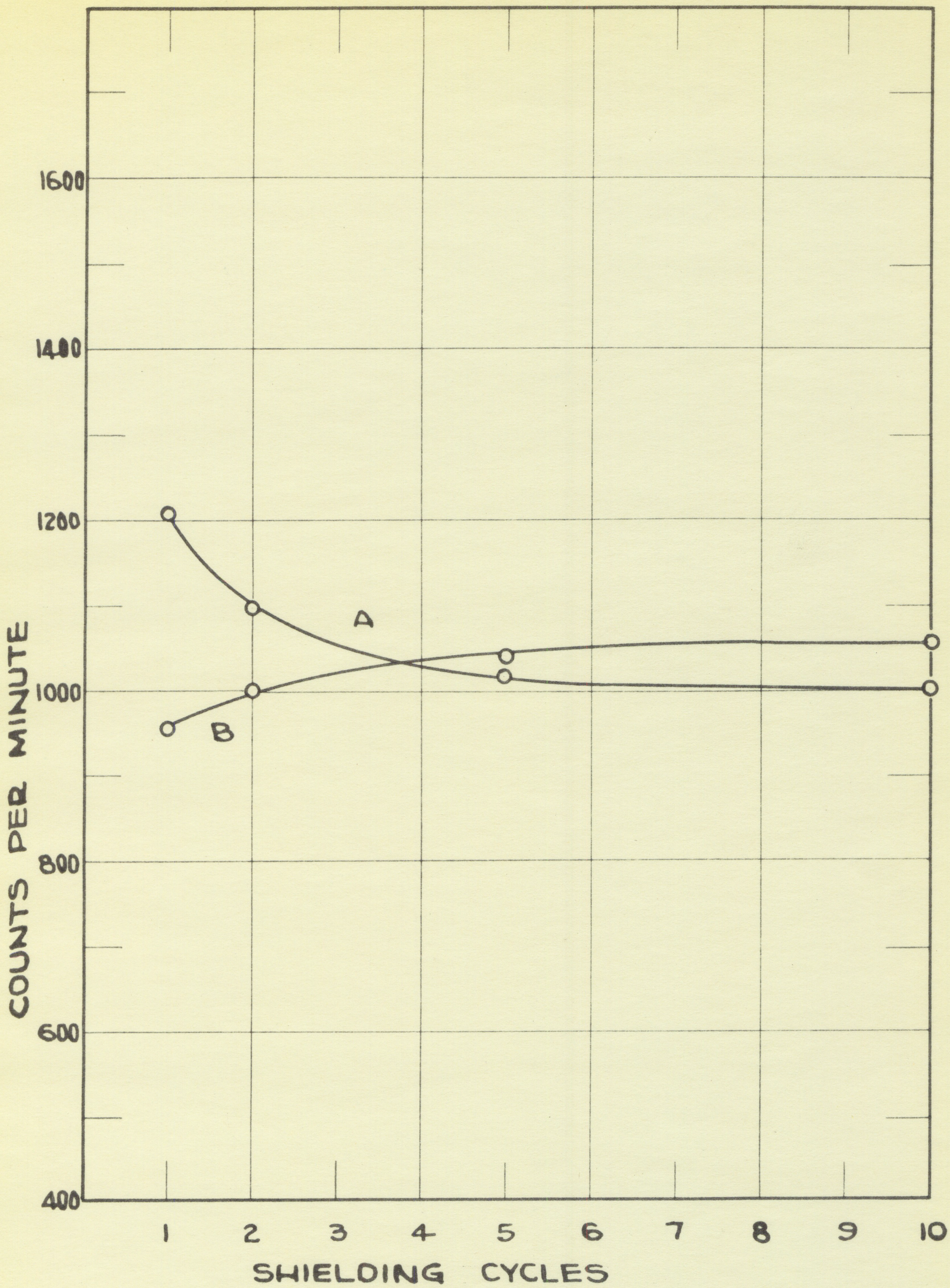


Figure 12. Gamma Counts for Boric Acid Solution.

source would tend to increase the counts. In taking data for curve B the lead was moved away from the source which would tend to decrease the counts. The increase in counts here indicates also that the more efficient positioning of the solution is the dominant effect. Examination of the points on curves A and B under the ten cycle arrangement brings out the action of the geometrical effect. With a ten cycle configuration under condition A, the lead is in a better position geometrically than in condition B. The solution, however, is less efficiently positioned in A than in B. The lower count at A shows that the geometrical effect is more important than the solution positioning at this degree of lamination.

B. Effects of Concentration of Neutron Absorber in Solution

1. Neutron shielding

The neutron counts taken under various fractions of the unit concentration are listed in Tables 7 and 8 and plotted in Figures 13 and 14. The slow neutron count shown in Figure 15 on a semi-log plot indicates that the drop is slighty less than the expected exponential decrease. If scattering were negligible and cross section constant the theory would predict an exponential

Table 7

Neutron Counts for Boric Acid Concentration Variation

Concentration	Slow Neutron Counting Rate	Fast Neutron Counting Rate
1	154 ± 4.4	259 ± 3.6
3/4	170 ± 4.3	274 ± 3.5
1/2	228 ± 4.9	298 ± 3.9
1/4	393 ± 6.8	346 ± 4.7

Table 8

Neutron Counts for Cadmium Sulfate Concentration Variation

Concentration	Slow Neutron Counting Rate	Fast Neutron Counting Rate
1	81 ± 2.5	242 ± 3.3
3/4	81 ± 2.4	248 ± 3.4
1/2	111 ± 3.0	251 ± 3.2
1/4	200 ± 4.2	254 ± 2.3
1/8	362 ± 6.3	256 ± 3.4

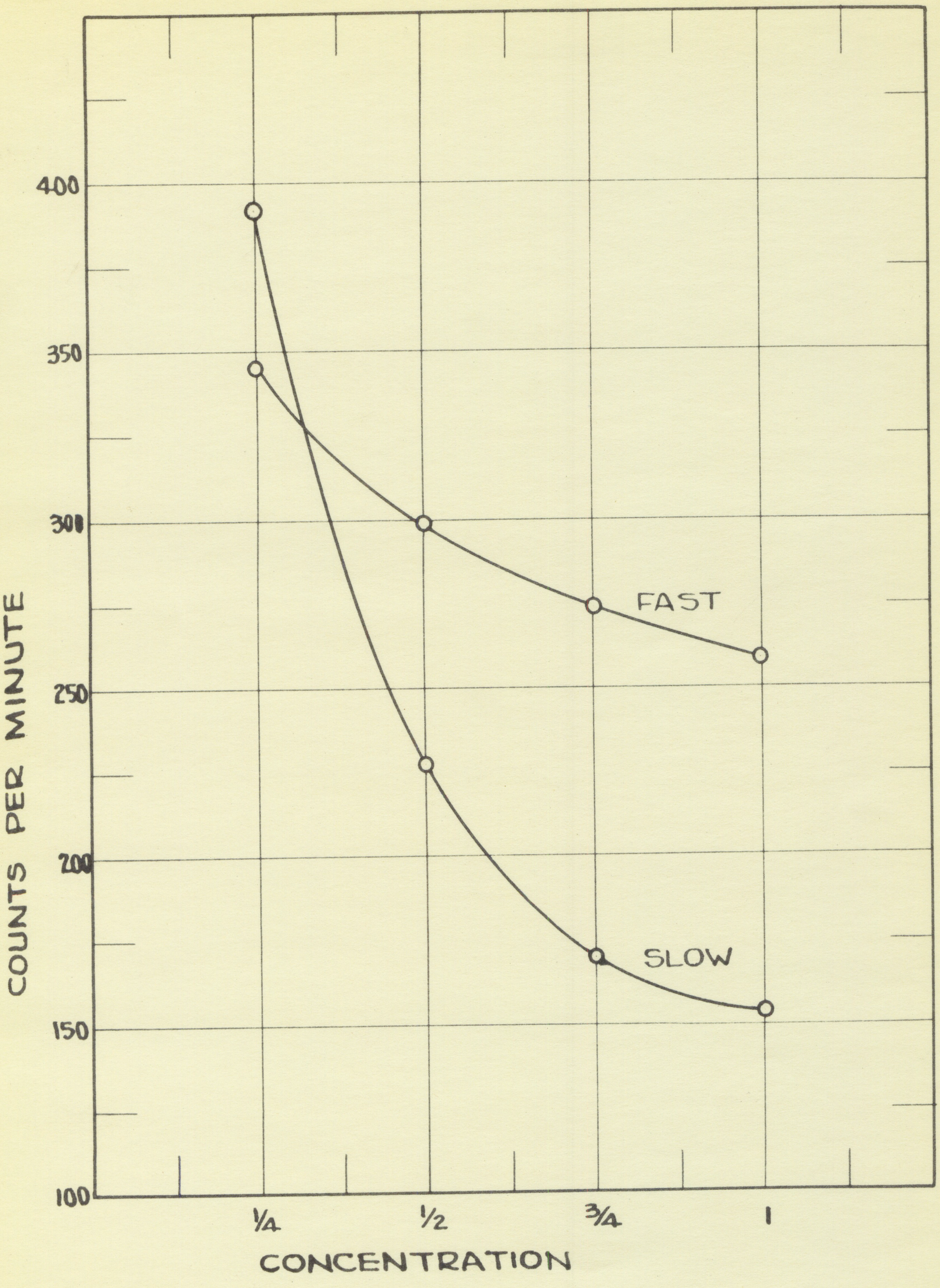


Figure 13. Neutron Counts for Boric Acid Concentration Variation.

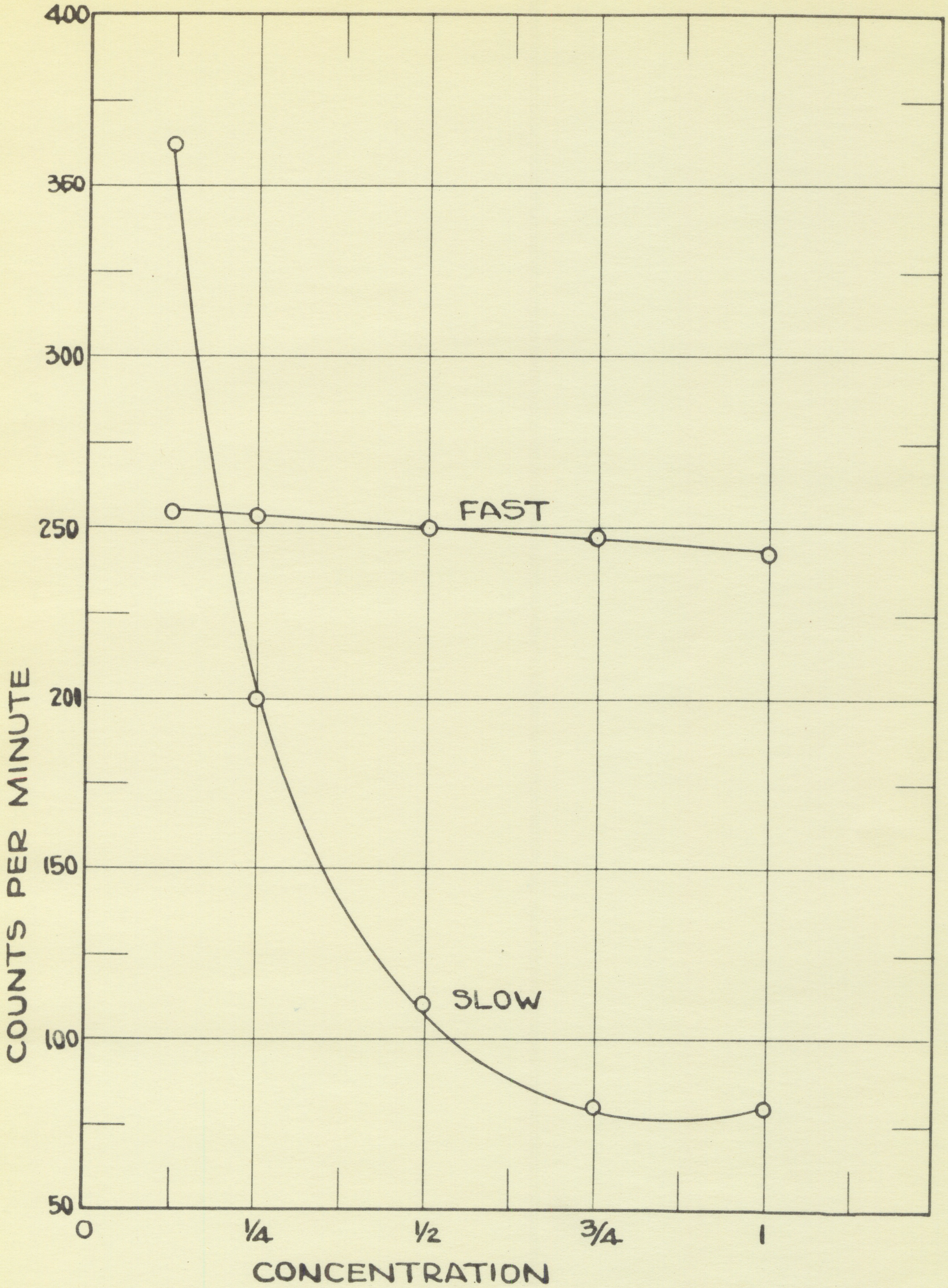


Figure 14. Neutron Counts for Cadmium Sulfate Concentration Variation.

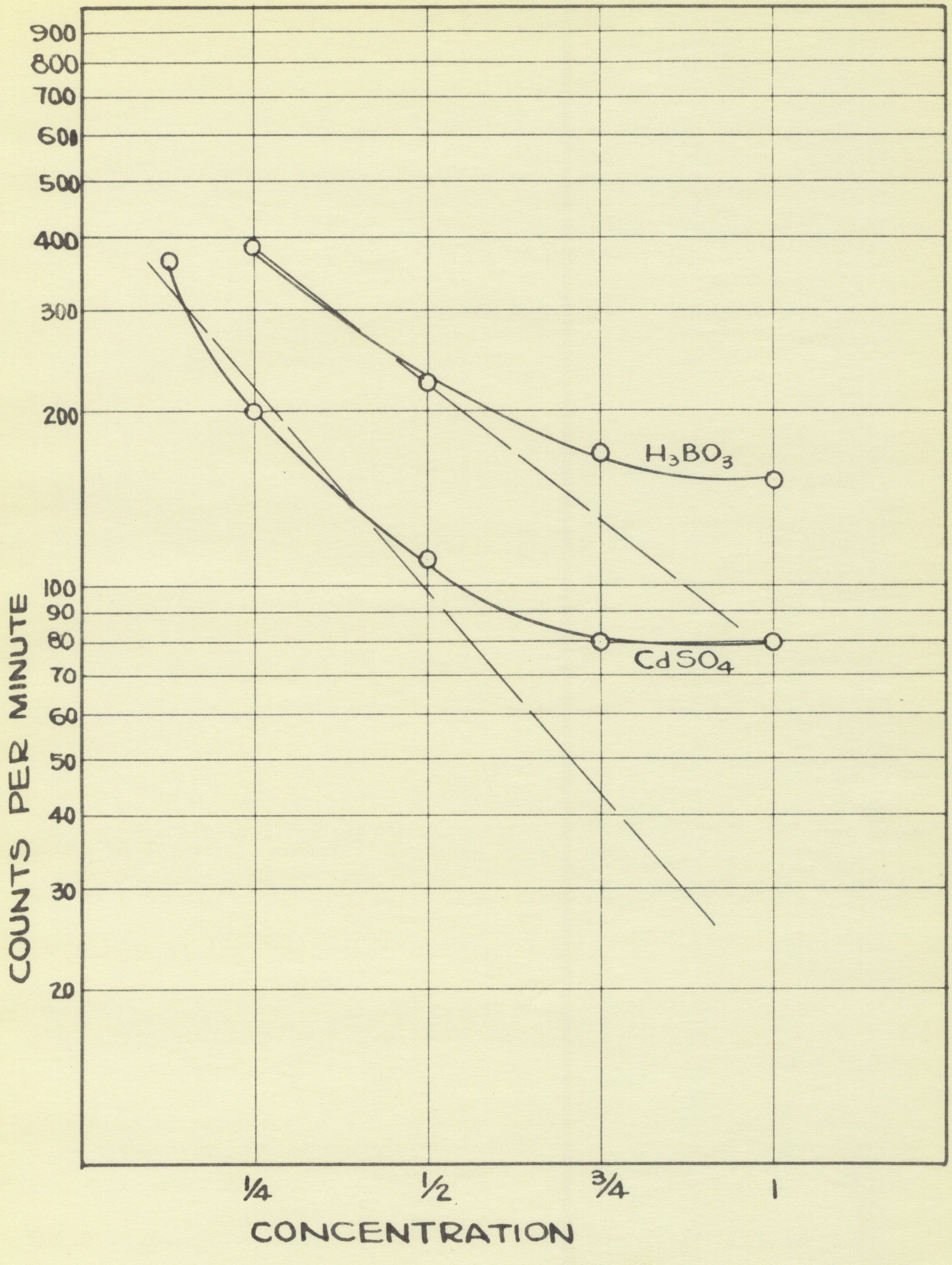


Figure 15. Slow Neutron Counts.

decrease in counts according to Equation 1.

$$I = I_0 e^{-\Sigma x} \qquad (1)$$

where:

I_0 is the initial neutron intensity.

I is the final neutron intensity.

Σ is the total macroscopic cross section.

x is the thickness of the material.

The slight deviation shown in Figure 15 is probably due to decreased scattering cross section as the neutron absorber is increased in concentration displacing more and more water. This decrease in scattering cross section would cause fewer neutrons to be scattered out of the system and also fewer to be thermalized into the high counting efficiency region of the boron tube. Since slow neutrons are defined here as including those from thermal energies up to 0.2 ev., this latter consideration is important. An inspection of the cross section curve for boron indicates an increase of over 100 per cent in the capture cross section for thermal neutrons over those at 0.2 ev.. Probably the most interesting point brought out by these curves is the fact that little change in the shielding effectiveness of the cadmium sulfate solution is made by increasing the concentration

Table 9

Gamma Counts for Various Concentrations

Solution	Concentration	Counting Time (Minutes)	Counts	Counting Rate $\frac{\text{Counts} \pm \sqrt{\text{Counts}}}{\text{Time in Minutes}}$
Boric Acid	1	10	10678	1068 ± 10.4
	3/4	10	10688	1069 ± 10.4
	1/2	11	11585	1050 ± 9.8
	1/4	10	10618	1062 ± 10.3
Cadmium Sulfate	1	8	11708	1214 ± 13.5
	3/4	8	11914	1435 ± 13.6
	1/2	9	13032	1504 ± 12.7
	1/4	12	17844	1487 ± 11.1
	1/8	10	14382	1438 ± 12.0

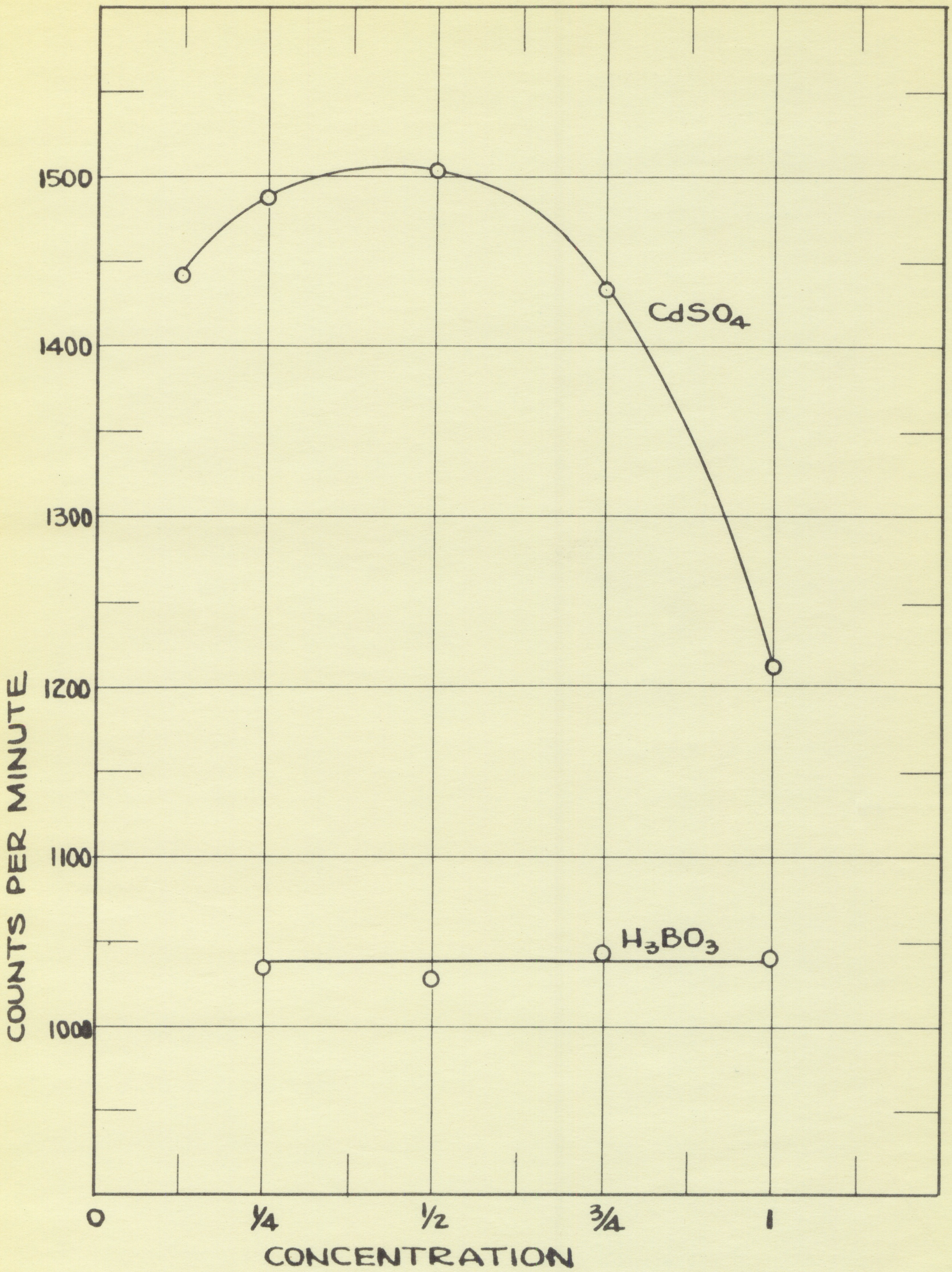


Figure 16. Gamma Counts for Various Concentrations.

above approximately ten per cent of saturation.

The general decrease in fast neutron counts is obviously due to the added absorber. The exact shape of these curves is difficult to explain, however, because of the lack of specific higher energy cross section data.

2. Gamma shielding

The gamma counts taken under various concentrations of the neutron absorber are listed in Table 9 and plotted in Figure 16. The nearly horizontal straight line obtained for the boric acid solution is expected since the addition of such a small amount of this compound would have little effect on the density of the solution and therefore little effect on the gamma shielding effectiveness. Having used so much more of the cadmium sulfate because of its higher solubility, one would expect some increase in the gamma shielding effectiveness because of the increased density and therefore increased mass absorption coefficient. This increase shows up in the decreased counts indicated by the curve. The small rise at the beginning of the curve is probably due to the emission of gammas by the cadmium atoms capturing neutron, these capture gammas subsequently being balanced by the increased density effect.

V. CONCLUSIONS

There appears to be justification for drawing the following conclusions concerning the shielding effectiveness of the materials used under the conditions described.

1. Starting from position A there is an approximately 15 per cent decrease in the slow neutron count, 20 per cent decrease in the fast neutron count, and 15 per cent decrease in the gamma count as the degree of lamination of the shield is varied from one cycle to ten cycles.

2. Beginning with position B there is an approximately 15 per cent increase in the slow neutron count, 35 per cent increase in the fast neutron count, and 10 per cent increase in the gamma count as the degree of lamination of the shield is varied from one cycle to ten cycles.

3. The data from which conclusions 1 and 2 were drawn also indicate that any change in the shielding effectiveness with changes in degree of lamination is probably due to a geometrical effect brought about by changes in position of the shielding elements.

4. With position B as the basic configuration there is an 80 per cent decrease in the slow neutron count as the cadmium sulfate concentration is increased from 1 per cent to 8 per cent by weight. This is greater than the decrease predicted by the exponential law.

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