REFLECTIVE TYPE SHIELDING FOR GAMMA RADIATION

by

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TABLE OF CONTENTS

I. INTRODUCTION

The problems of shielding for nuclear reactors may be resolved into two general categories. These categories pertain to the problems involving shielding against neutrons and the problems involving shielding against gamma radiation. Particles other than neutrons and gamma rays which are emitted during the nuclear processes may be ignored since the penetrating power of any of these particles is much less than that of either the neutrons or the gamma rays. Hence, a shield designed to attenuate neutrons and gamma rays will be more than ample to stop other forms of radiation as well.

Neutron shielding involves two processes, namely the slowing down or moderation of the neutrons and the capture of these slow or thermal neutrons. While hydrogen and other elements of low atomic weight are effective neutron moderators, they are not used exclusively in neutron shielding since they have rather low scattering cross sections for neutrons of high energies. In order to slow the high energy neutrons which are emitted in the fission process, materials of a moderate to high density, such as iron or lead, are sometimes used in conjunction with the lower density moderators. This higher density material can slow the neutrons from high energies down to about 0.5 Mev through inelastic scattering collisions. The material is placed around a reactor as the innermost portion of the shielding and it is referred to as the thermal shield because of the large amounts of energy it must absorb. As it does have a moderate to high density, it is also a rather effective gamma ray shield and hence must be capable of absorbing some energy of the gamma rays as well as a considerable portion of the energy of the neutrons. The thermal shield is not always used, and its actual value has been the subject of some investigation (1). After slowing down to about 0.5 Mev energy, the neutrons are readily susceptible to moderation to thermal energies through elastic collisions with the nuclei of the lighter moderating materials. These materials form part of the biological shield of the reactor, which constitutes the outer portion of the shielding if a thermal shield is used. For the capture of the thermal neutrons, a material with a high capture cross section may be used. One of the best of these is boron-10 which has a thermal neutron capture cross section of 3990 barns. This substance has the added advantage of emitting alpha particles rather than gamma rays after the neutron capture. Thus, no new gamma rays are created and the capture of the neutrons does not add to the overall problems of shielding the reactor.

In contrast to the general requirements of neutron shielding, i.e., the use of low density materials, gamma shielding requires the use of high density materials. Currently accepted methods of shielding against gamma radiation involve the placement of high density material in the path of the gamma rays. The gamma rays are attenuated in the material by a combination of the processes of photoelectric effect, Compton scattering and pair production, depending upon the energies of the gamma rays and the type of material used for the shield. The amount of the attenuation is a function of both the density and the thickness of the material. Thus, lead makes an effective shield due to its high density. High-density concrete is also used for this purpose. However, as the density of the concrete is less than that of lead, the concrete shield must be thicker than the equivalent lead shield. The total mass of the material in the path of the gamma rays must be approximately the same, regardless of the type of material, in order to attain the same attenuation of the gamma radiation.

The use of lead permits a more compact arrangement inasmuch as the high density of the lead allows an effective shield to be constructed that is not excessively thick. However, the physical properties of lead are such that it cannot carry any appreciable portion of the reactor load, and its melting point is so low that it cannot be subjected to high temperatures. Concrete, on the other hand, has to be three or more times as thick as an equivalent lead shield, depending upon its density, and hence requires a considerably larger area for construction, but it can carry a large portion of the reactor load and can be subjected to relatively high temperatures without danger of structural damage. For stationary reactors, concrete is generally preferred to lead for construction of the general gamma ray shield because of its better physical properties, its generally lower cost and its ease of placement. The lead shielding is usually reserved for special situations such as temporary shielding around a particular portion of the reactor.

Although the space available for shielding, the relative costs of the shielding materials and their physical properties have been the primary considerations involved in the selection of reactor shielding to date, present developments in the nuclear power reactor field have introduced the additional problem of the weight of the shielding materials. The U.S. Army, as well as other organizations, is interested in the development of "Package" power reactors which can be transported to remote areas and utilized there to provide power. The U.S. Air Force is working on a propulsion system for aircraft which utilizes nuclear power. The U.S. Navy is already using nuclear powered submarines and is working toward nuclear propulsion of other vessels. Railroads are thinking in terms of nuclear powered locomotives. In all cases where the reactor is to be used as a propulsion unit for some mobile type of equipment, or where the reactor unit should be capable of being easily transported, both the weight and the space of the shielding for the reactor become a major problem.

As neutron shielding can be accomplished with rather low density materials and with small thicknesses of neutron absorbers, it appears that if any appreciable savings are to be realized in either weight or space, or preferably both, then these savings must come from an improved type of gamma ray shield. It is the purpose of this study to investigate the possibility of developing a reflective type shield for gamma radiation.

II. REVIEW OF LITERATURE

When Roentgen first published his announcement of the discovery of X-rays, he stated that, among other properties, the X-rays could not be reflected or refracted. However, subsequent research demonstrated that both reflection and refraction could occur under certain special conditions.

Stenström (2) found that when X-rays whose wave lengths are greater than about 3 Å are reflected from crystals of sugar and gypsum, Bragg's Law does not give accurately the angles of reflection. He interpreted the difference as being due to an appreciable refraction of the X-rays as they enter the crystal.

Compton (3) reasoned that the deviations in Stenström's experiments indicated that the index of refraction of the crystals was less than unity. He further reasoned that if this were also the case with other substances, then X-rays striking the substances from the air at sufficiently small glancing angles should be totally reflected. Following this reasoning, he proved that total reflection could be effected by using a polished plane surface with the X-rays incident thereon at small glancing angles.

Later, Doan (4), following the method of Compton, worked with X-rays of various wave lengths to determine their critical glancing angles from some metallic mirrors. The mirrors were made by sputtering the metals onto highly polished optical glass surfaces. Some of Doan's results are shown in Table 1.

Table 1. Critical angles for reflection obtained by Doan[a]

Wave lengths of X-rays	Type of metallic mirror	Critical angle
1.537 Å	Copper	20' 34"
1.537 Å	Silver	26' 42"
1.537 Å	Nickel	24' 40"
1.537 Å	Gold	31' 24"
1.389 Å	Copper	19' 36"
1.389 Å	Nickel	16' 9"
0.7078 Å	Steel	9' 35"
0.7078 Å	Nickel	10' 15"
0.7078 Å	Silver	11' 42"

[a] Data extracted from Table 1, Doan (4, p. 107)

Although it was thus demonstrated in the early 1920's that reflection of X-rays is possible, the principle of reflection does not appear to have been applied for shielding purposes. This has no doubt largely been due to the very small critical angles involved. For example, the highest critical angle indicated in Table 1 would result in a total deflection of only about 1 degree from a plane surface. This amount of deflection is hardly enough to be useful for any practical shielding purpose. However, in 1947, Proell (5) used the property of reflection of the X-rays to develop a theory for reflective type gamma ray shielding.

Proell's theory is based first of all upon the assumption that gamma rays will behave similiarly to X-rays. This is certainly a valid assumption inasmuch as the two types of radiation are essentially the same, differing only in their methods of production.

Proell reasoned that since gamma rays and X-rays are essentially identical, the materials investigated by Doan, and probably other materials as well, would also show a refractive index of less than unity for gamma radiation. However, as a single reflection of the gamma ray would not produce a deflection of a usable amount, he proposed that the plane surface used for reflection be curved into a quarter circle. A gamma ray striking the curved surface at or below the critical angle should be reflected, just as from a plane surface. However, after the first reflection, it should strike the surface again and suffer a second reflection. This process should continue until the gamma ray has followed the entire curve of the surface, i.e., until it has undergone a 90 degree deflection from its original path.

As the energies of gamma rays would be generally higher than the X-ray energies used by Doan, the wave lengths of the gamma rays would be smaller, and hence, judging from the results obtained by Doan, the critical angles for reflection would also be smaller. Proell assumed that curves of the values obtained by Doan would extrapolate to shorter wave lengths and still show critical angles for reflection.

Figure 1 is a schematic drawing of a gamma ray of energy E incident upon a curved surface AD from a source S, where AD forms a quarter circle. It is assumed that the gamma ray originally strikes the curved surface at

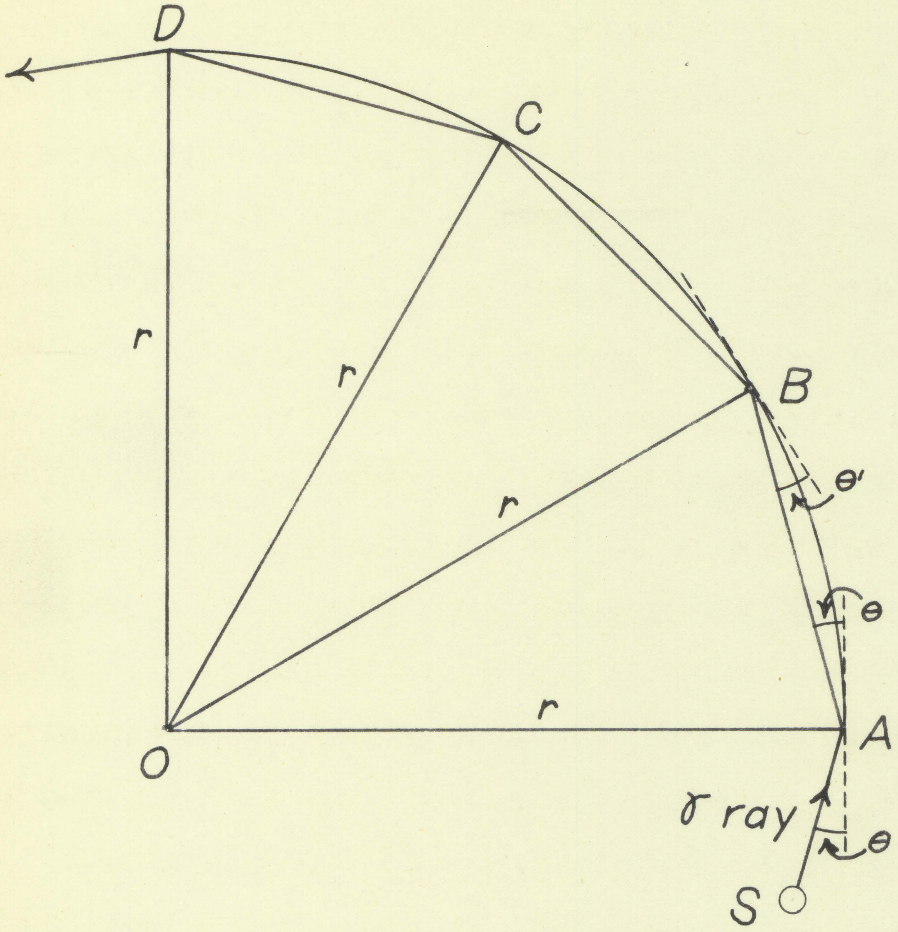

Fig. 1. Path of gamma ray after being once reflected from curved surface

A, making an angle θ with the tangent to the surface at this point, where θ is equal to or less than the critical angle for reflection. Since the angle of incidence is within the limiting conditions for reflection, the gamma ray will be reflected, and, as the angle of reflection must equal the angle of incidence, the angle of reflection will also be θ. The gamma ray will then follow a straight path AB which is a chord of the curved element, striking the surface again at B and making an angle of θ' with the tangent to the surface at this point. It is evident that angle OAB must equal 90° - θ, since the radius OA is perpendicular to the tangent at A. Similiarly, the angle OBA must equal 90° - θ'. Triangle AOB is an isosceles triangle since OA and OB, the radii of the curved surface, must be equal. Hence, angle OAB must equal angle OBA and consequently θ' equals θ. The same procedure may be followed to show that all angles of incidence and all angles of reflection are equal, and, by observing that triangles AOB and BOC are identical, that the points of incidence on the curved surface are connected by chords of equal length.

In accordance with the foregoing, it is therefore postulated that once a gamma ray has struck the curved surface at or below the critical angle, it will undergo a series of reflections until it has been deflected from its original path by 90 degrees.

It is apparent, however, that one such curved element could not deflect more than a very small portion of the incident gamma rays. Froell therefore proposed a double bank of curved elements stacked closely together as is indicated in Figure 2, which is a cross sectional view of the elements.

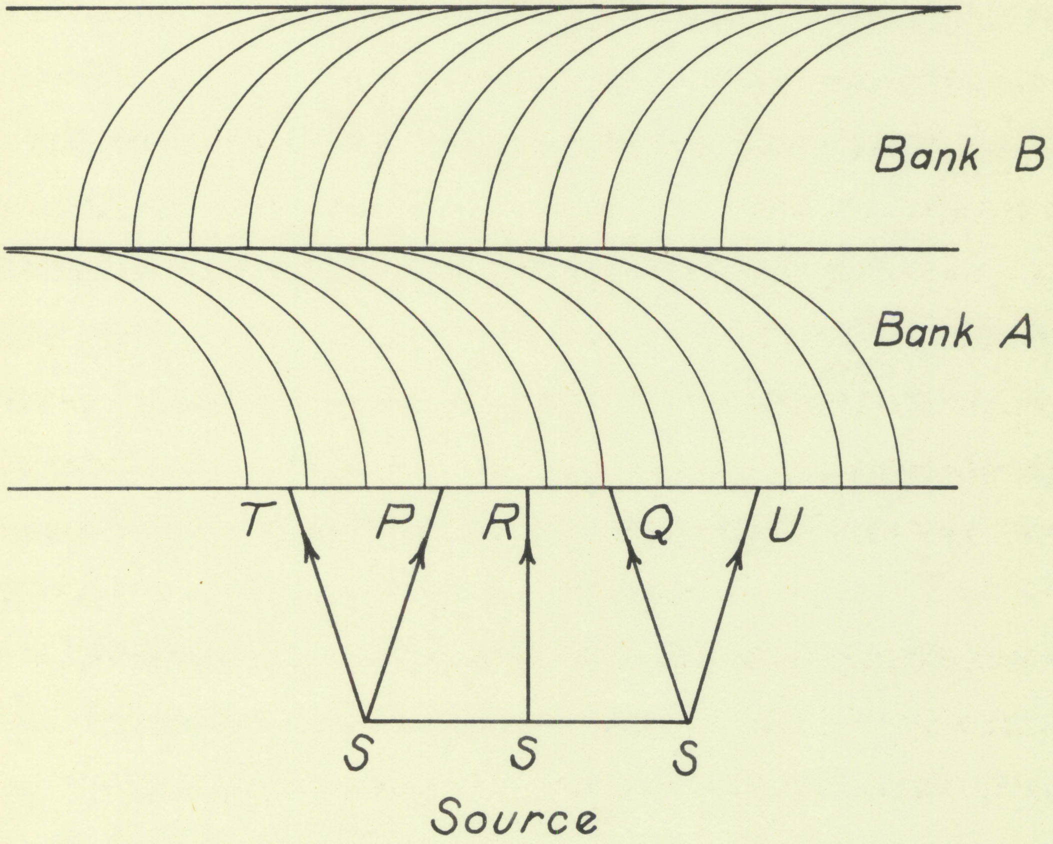

Fig. 2. Proposed arrangement of foils in two banks to form complete shield[a]

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[a] Figure adapted from Proell (5, p. 23)

In the figure, bank A would deflect all gammas incident normal to the bank, such as SR, and all gammas incident from the right, such as ST and SQ. However, gammas striking from the left, such as SP and SU, would in all cases strike the elements of bank A at angles greater than the critical angle and would therefore pass through the bank without reflection. Upon entering bank B, the gammas would penetrate until they were incident upon a surface at less than the critical angle, at which point they would be reflected and would then follow the curve of the elements in B until they were totally deflected. Thus, all gammas would be deflected either to the right or to the left and none would penetrate the shield. This, of course, ignores the possibility that the gamma rays might undergo scattering collisions with the material of the curved elements and be scattered in the forward direction such that they would penetrate the shield. It is evident that only the components of direction of the gammas which lie in the plane of the paper need be considered since other components do not affect the angles of incidence on the curved elements.

In order to have an impermeable shield, all incident gamma rays must be totally deflected. Proell established the condition for impermeability as that in which all normally incident rays would be reflected. He determined that normal rays would strike the shield at the most unfavorable angles for reflection to take place. The condition for impermeability would be established only when the curved elements were stacked closely enough to deflect all normally incident gamma rays.

Figure 3 shows a cross sectional view of two curved elements BC and DE of the shield. It is evident that the most unfavorable ray, not

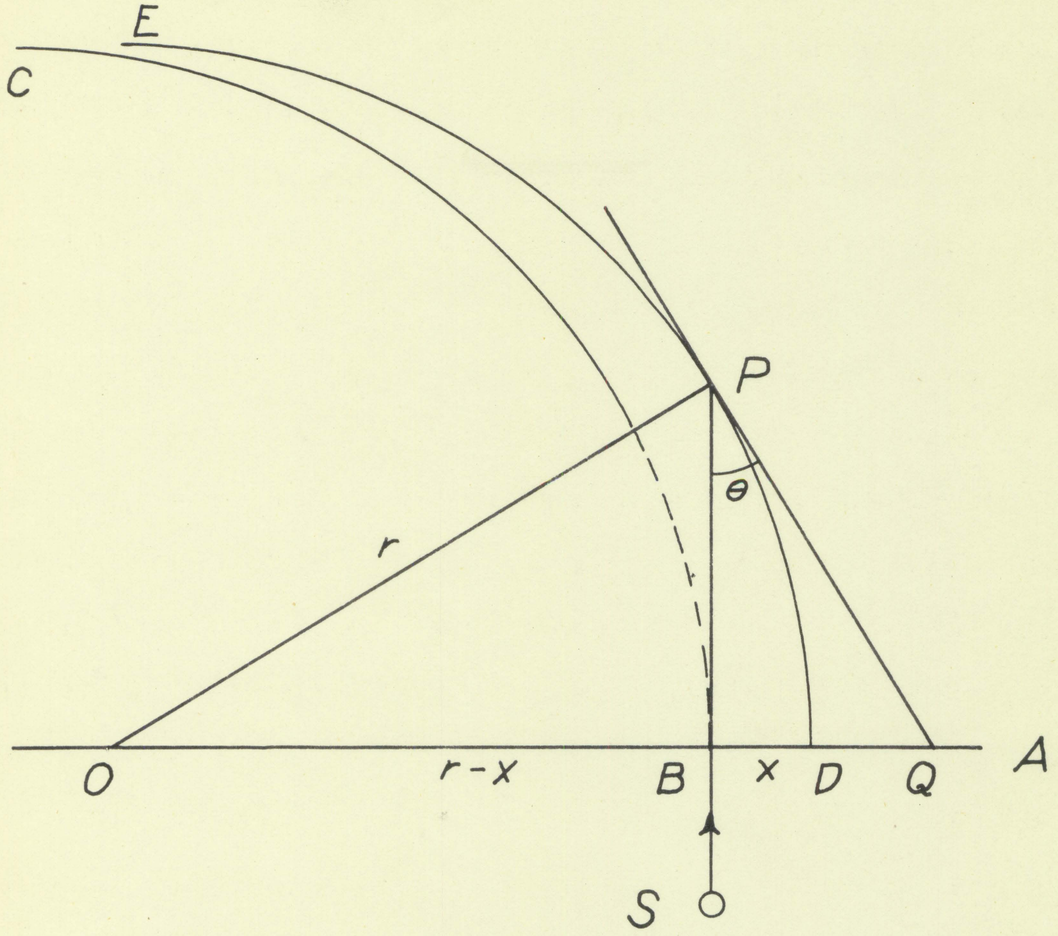


Fig. 3. Incident gamma ray striking shield at the most unfavorable point

considering a ray striking from the left, would be normally incident upon the plane OA, formed by the leading edges of the curved elements, and would just clear element BC. The ray would then strike element DE at a point P, making an angle θ with the tangent to the element at P. If reflection is to occur, then θ must be equal to or less than the critical angle. If x is the distance between the curved elements along OA and r is the radius of curvature of the elements, then from the figure

$$\angle BOP = \cos^{-1} \frac{r - x}{r}$$

But angle BOP equals θ and therefore

$$\theta = \cos^{-1} \frac{r - x}{r}$$

Let us assume, for the purpose of calculating the order of magnitude of the distance x, that θ, the critical angle, is, in this case, 12 minutes and that the radius of curvature of the curved surfaces is 5 centimeters. It therefore follows that

$$12' = \cos^{-1} \frac{r - x}{r}$$

or

$$\cos 12' = \frac{r - x}{r}$$

Since the cosine of 12' is 0.9999939

$$0.9999939 = \frac{5 - x}{5}$$

From which

$$x = 0.0000305 \text{ cm}$$
$$= 3050 \text{ Å}$$

This value is a measure of the order of magnitude of the initial spacings between curved elements. From the calculations, it is seen that if either the critical angle or the radius of curvature of the elements is increased then the maximum element spacing for impermeability also increases.

It is evident that if the spacing between elements is to be of the order of 3050 Å, then the element thickness must be less than this amount, preferably by a factor of at least two. Consequently, it is required that the elements must be very thin foils of the material to be used as a reflector. However, making foils with a thickness of less than 3050 Å is an extremely difficult task with present engineering techniques.

Proell suggested as a possible alternative to the foils, the use of crystals to deflect the gamma rays. In general terms, the spacing between atomic planes in crystals is of the order of 3 - 5 Å. Thus, if a suitable crystal could be found which could be bent into an arc of 90 degrees, with the crystal planes following the shape of the crystal, then the crystal planes could be used as the curved reflecting surfaces. Such an arrangement should give an excellent shield since the spacing between crystal planes is less than the 3050 Å calculated previously by a factor of approximately 1000.

III. PURPOSE OF INVESTIGATION

The theory of the reflective type shield, as developed by Proell, was not verified experimentally. However, the need for an improved type of gamma ray shielding for nuclear reactors appeared to justify an experimental investigation of the theory.

The purpose of this investigation, then, was to test Proell's theory under rather idealized conditions to determine if large angle deflections of gamma rays could actually be obtained. It was felt that the results obtained would indicate whether or not further effort should be devoted toward the development of a practical, reflective type gamma ray shield.

IV. MATERIALS AND APPARATUS

A. Source of Radiation

The experimental work was conducted using a cobalt-60 source with a nominal strength of 100 microcuries. The source was contained in an aluminum wafer whose dimensions were 1/8 inch in thickness and 1/2 inch in diameter. The source covered a circular area approximately 1/8 inch in diameter at the approximate center of the wafer. The wafer had a small ring attached to one face which allowed a string to be attached to the wafer for safe handling. On the edge of the wafer, at the ends of a diameter, were placed two small steel set screws which allowed the wafer to be handled with magnets.

Cobalt-60 decays by emission of a beta particle of 0.31 Mev energy, followed by two gamma rays with energies of 1.33 Mev and 1.17 Mev respectively. Beta particles of 0.31 Mev energy can be stopped by 0.01 inch of aluminum. Hence, the thickness of half of the aluminum wafer surrounding the source was more than ample to stop all betas emitted. As the source strength of Co^{60} is measured by the number of disintegrations per unit time, the number of gamma rays emitted is twice the value of the source strength. Thus, the source was effectively 200 microcuries of gamma radiation. As the gamma rays from Co^{60} have very nearly the same energies, 1.33 Mev and 1.17 Mev, they may generally be considered as having an average energy of 1.25 Mev. Hence, for the purpose of this experiment, the source may be considered to have been a nominal 200 microcuries which emitted only gamma rays with an average energy of 1.25 Mev. The half life of Co^{60} is 5.2 years. Thus, any decrease in the source activity during the course of an experimental run was negligible.

In order to use the source in the experimental apparatus, a lead cylinder 3 1/8 inches in diameter and 4 1/2 inches high was cast. At a distance of 2 1/2 inches from the bottom of the cylinder, a 5/8-inch hole was drilled along a diameter of the cylinder to a depth of 1 1/16 inches. The aluminum wafer containing the source was placed in this hole with the longitudinal of axis of the wafer parallel to the axis of the hole. Thus, the source was essentially 1 inch from the circumference of the cylinder, and, while the gamma ray emission was unimpeded along the hole, the gamma rays were attenuated by the lead in all other directions.

Dosage rates, based on the nominal source strength, were calculated to be a maximum of 45.6 milliroentgens per hour at the surface of the lead cylinder for that portion of the cylinder which was touched during adjustments, and 3.76 milliroentgens per hour at a distance of 2 feet from the source in line with the open hole in the cylinder. The lead cylinder was handled twice daily when experiments were being conducted, for about 30 seconds during each operation. The cylinder was grasped from the rear so that at least 1 inch of lead was shielding the hand from the source. The maximum daily dose to the hand from this handling was thus less than 1 milliroentgen. While conducting the experiments, the source was often approached to within a distance of 2 feet, and manipulations of the reflective foils and the counter tube were made at approximately this distance. Whole body dosage was reduced to a negligible amount during these times, however, due to the attenuation of the gamma rays by approximately 4 inches of lead which was used to collimate the gamma ray beam and to reduce stray gamma scattering. During the manipulation of the foils and counter tube, the hands were often in the direct beam from the source, but only for short periods of time. Total daily exposure of the hands was less than 1 hour so that the maximum daily dose was of the order of 3.5 milliroentgens. During periods between manipulations, the observer was normally located at a distance of about fifteen feet from the source and was protected from the source by the lead shielding of the collimator arrangement. The dosage received during these periods was less than 0.0001 milliroentgens per hour and was thus negligible. The maximum weekly doses received during the course of the experimentation were then on the order of about 25 milliroentgens to the hands and not more than about 3 milliroentgens of whole body dosage.

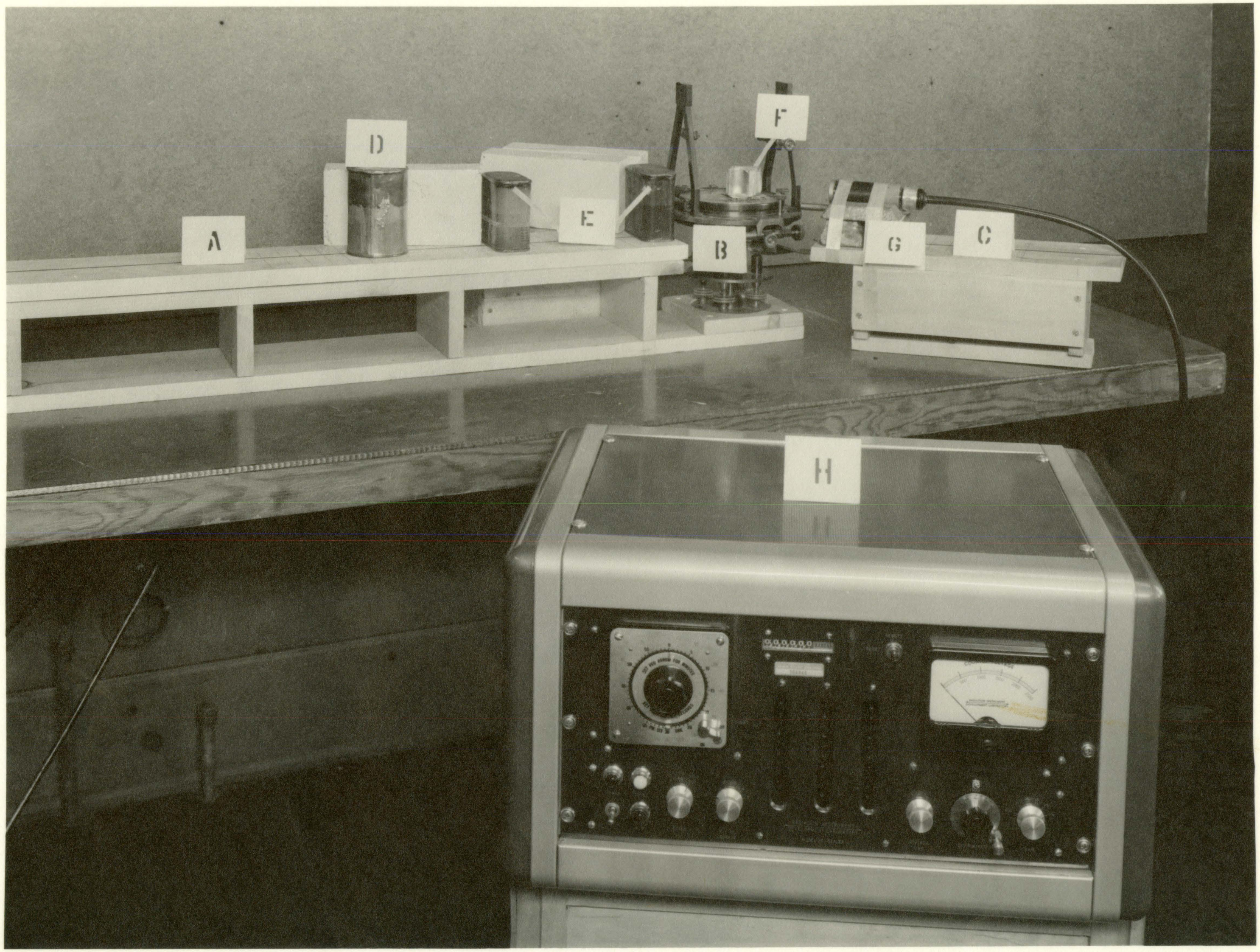
It was not deemed necessary to wear film badges, dosimeters or other types of radiation monitoring devices because of the low radiation level from the source. Measurements were made periodically of the dosage level of the surroundings with a model 2612 Portable Survey Meter manufactured by the Nuclear Instrument and Chemical Corporation. Readings obtained with this instrument indicated a negligible dosage level in the laboratory.

B. Description of Apparatus

A photograph of the experimental apparatus is shown in Figure 4. The apparatus consisted essentially of three parts. First, there was a wooden

Fig. 4. Experimental apparatus

A. Source and collimator platform
B. Transit
C. Counter tube platform
D. Container for source
E. Collimator blocks
F. Foils
G. Counter tube
H. Scaler


A
D
E
B
F
G
C
H

platform 6 inches in width and 52 inches long. The top of the platform was 6 inches above ground level. Second, at the end of the platform and affixed to the same board which acted as a base for the platform was a transit less the telescope. It was so situated that the glass face of the compass scale was approximately 7 3/4 inches above ground level. Third, there was a counter tube platform which was 6 inches wide, 18 inches long and stood 6 inches above ground level.

The long platform was designed to accommodate the gamma ray source in its lead container together with collimators and lead blocks which were necessary to collimate the gamma ray beam and to stop any stray radiation from the source from reaching the counter tube. Two boxes, serving as auxiliary platforms, were placed near the transit end of the long platform to aid in supporting the lead blocks used for shielding.

The transit, an early model produced by W. & L. E. Gurley, was used as a convenient means of measuring small angles. The reflective foils were affixed to the glass top of the compass scale by means of wax. The glass top of the compass scale rotated with the vernier for the compass. Thus, the foils could be adjusted to any desired position within a plus or minus ten degrees for the optimum angle of incidence of the gamma rays. By using the vernier of the compass scale, angles of 5 minutes could be easily read and changes in angle of 1 minute could be made, although with some difficulty and with a probable error of plus or minus 30 seconds.

The counter tube platform was designed to hold the counter tube and any necessary supports or shielding in a position which could be readily reproduced in the event the tube had to be moved. The platform was at a fixed distance from the swivel axis of the transit and was held in position by a length of 1/8-inch by 3/4-inch strap iron which was firmly affixed to the platform on one end and joined to a brass collar encircling the cylindrical brass support of the transit on the other end. By using this arrangement, the platform could be rotated to a plus or minus 100 degrees, using the swivel axis of the transit as the axis of rotation. A tube, mounted on the platform and initially aimed at the swivel axis of the transit, was thus always at the same distance from and aimed at the swivel axis. A 3/8-inch by 6-inch cylindrical, Alnico bar magnet, mounted at the transit end of the platform attracted the compass needle of the transit. The amount of rotation of the platform could thus be measured in degrees with an accuracy of about plus of minus 1 degree.

The overall apparatus was designed so that a source and collimators could be mounted at any desired position along the long platform. The collimated beam of gamma rays would thus be aimed down the platform toward the transit. On the glass compass face of the transit could be mounted the bank or banks of reflective foils which could be adjusted accurately by means of the compass vernier to the optimum angle of incidence of the gamma rays. Under the assumption that the gamma rays would actually suffer a large angle deflection, the counter tube platform was designed so that the tube could be adjusted to either side of the foil bank in order to obtain a measurement of the amount of deflected radiation. The platform was made to rotate about the transit so that the tube would always be at the same distance from the transit swivel axis and hence from the reflective foils. It would also be constantly aimed at the swivel axis of the transit. Thus, repeated manual measurements of distances and angles were eliminated and good reproducibility was insured.

C. Collimators

The collimators used consisted of two lead blocks which were cast with the dimensions of 3 5/8 inches by 3 5/8 inches by 1 7/8 inches. Holes 3/16 inch in diameter were drilled through the blocks in the direction of the thickness, at a distance of 2 1/2 inches from the bottoms of the blocks and midway between the sides. The blocks were then placed so that the axes of their holes lined up with the axis of the hole drilled in the cylindrical block which contained the source. Thus, a collimated beam of gamma rays 3/16 inch in diameter was obtained.

For gamma rays with an energy of 1.33 Mev, the half thickness of lead is approximately 1 centimeter. Thus, the two collimator blocks were equivalent to about 5.5 half thicknesses and reduced the gamma ray intensity by about 97% in directions other than along the line of the holes.

Lead shielding blocks were used in conjunction with the collimator blocks to insure that no gamma rays could by-pass the collimators and still strike the counter tube. This, of course, does not include those gammas which might be scattered from the walls or fixtures of the laboratory and strike the tube. However, the counting rate produced by these scattered gamma rays was considered to be essentially constant inasmuch as the overall geometry of the source and tube did not vary appreciably with respect to the laboratory during the conduction of an experimental run. Thus, the counting rate produced by these scattered gamma rays was considered to be part of the background activity.

It should be noted that the choice of 3/16 inch as the diameter of the holes in the collimator blocks was largely dictated by the source strength of the Co^{60}. In order to attain fair collimation and still obtain a usable counting rate from the counter tube, the holes had to be large enough to pass a reasonable number of the emitted gamma rays. It would be preferable to have smaller holes used in conjunction with a larger source.

D. Foils

Aluminum foil was used in the experimental work. Although aluminum was not tested for reflective properties by Doan in his experiments, it was assumed that aluminum would exhibit the same properties as other materials tested by Doan. It was further assumed that the critical angle of the aluminum for reflection of the gamma rays is of the same order of magnitude as the angles determined by Doan for other materials.

Aluminum foil was used primarily because it was the only foil which was readily available, other than platinum and gold foils, in the thickness desired and in the quantity required. The foil used was 0.00045 inches thick and was obtained from the Fisher Scientific Company in 3-inch rolls which held a 210-foot length of aluminum. Although the foil thickness was much larger than the order of magnitude calculated for the fabrication of an impermeable shield, it was felt that there would still be some indication of reflection from the foil bank.

The foil banks tested all consisted essentially of a quarter circle section of foil which had been spirally wrapped about a cylinder. Although this was not strictly in conformance with the theoretical design, where the foils have the same radii of curvature, it was felt that this method of fabricating the foil bank offered the best available means of obtaining a reasonably accurate configuration with a minimum of crinkling of the individual foils.

For preparation of foil number 1, 120 pieces of aluminum foil with dimensions of 3/4 inch by 1 inch were stacked on top of one another and the stack was then molded around the circumference of a 3/4-inch diameter cylinder. The foils were held together and in their curved position by means of wax.

Foil number 2 was prepared in the same manner as foil number 1 except that the layers of foil were alternated with layers of bond paper. The molding of the foil was done around a 1 1/4-inch diameter cylinder.

Foil set number 3 was prepared by spirally wrapping a 1 1/2-inch by 50-foot piece of foil around a 1 3/16-inch diameter cylinder. Successive layers of aluminum foil were separated by a thickness of manifold paper. The ends of the roll were glued into position and the roll was then cut at the quarter points. Thus, four essentially identical foil banks were obtained, each with a total curvature of approximately 90 degrees.

Foil set number 4 was prepared similiarly to foil number 3 using the same amount of aluminum foil. However, it was wrapped about a 3/8-inch diameter cylinder and the layers of aluminum were not separated from one another.

In the preparation of foils 1 through 4, it was felt that excessive crinkling of the foil had been produced through the handling and wrapping procedures. Therefore, a fifth set of foils was prepared using a different technique.

Foil set number 5 was prepared by utilizing the aluminum foil as it had been received from the manufacturer. At the time of foil preparation, the roll of aluminum was in the form of a 3-inch roll approximately 150 feet in length, wrapped around a cardboard cylinder with an outer diameter of 1 1/2 inches. This 3-inch roll was first cut in half, producing two 1 1/2 inch rolls. One of these small rolls was then cut at the quarter points, producing four individual foil banks, each curved through a quarter circle.

As explained in the test procedure, the four foil banks in each of sets 3, 4 and 5 were combined and used as single reflecting banks.

E. Accessory Apparatus

The counter tube used for determining counting rates was a 3.5 mg/cm^2 mica, end window counter, serial number 27838, manufactured by the Nuclear Instrument and Chemical Corporation. It was operated with a metal cap over the mica window, since the gamma rays could easily penetrate the cap while the cap protected the window from injury. The operating voltage of the tube was 925 volts.

The tube was connected by an appropriate lead to a model 200, decade scaler, manufactured by the Radiation Instrument Development

Laboratory. The scaler had a built-in timer, allowing counts of up to 1 hour duration to be taken. The accuracy of the timer was not checked, but as all counts were made utilizing the timer, and as only relative counting rates were desired, the only requirement was that the timing be consistent. The scaler was operated with a gain setting of 1/16 and a discriminator setting of 60. These settings were found to give the most consistent results. It should be noted that with higher gain settings, the scaler was quite sensitive to both vibrations and the flicker of the fluorescent lights in the laboratory.

A model 2612 Portable Survey Meter manufactured by the Nuclear Instrument and Chemical Corporation was used to monitor the radiation level within the laboratory.

F. Crystal Reflectors

As mentioned earlier, Proell suggested that perhaps crystals could be used in the reflective type shielding. His theory was that by bending a crystal with appropriate dimensions through an arc of 90 degrees, the atomic planes of the crystal could be used as the reflecting surfaces.

This matter was the subject of some investigation during the early stages of this experimental work. The investigation did not result in finding crystals capable of being bent through an arc even approaching 90 degrees. The structure of those crystals which can be slightly deformed usually changes during the course of any large deformation so that even though a crystal had atomic planes parallel to the surface of the crystal before deformation, these planes would not necessarily form elements of concentric cylindrical surfaces after deformation.

For this reason, the possibility of using crystals was eliminated at the outset of the experimental work. It does not necessarily follow, however, that the idea of using crystals should be discarded. There may be crystals which can be procured in the quantities desired which would be suitable for fabrication of a shield.

V. PROCEDURE

A. Experimental Arrangement

A number of factors affected the experimental arrangement of the source, collimators, foils and counter tube. Two of these factors, the counting rate and the amount of collimation, are inversely related, so that, for a source of given strength, an increase in the counting rate requires a decrease in the collimation.

In the conduct of the experiment, a well collimated beam of gamma rays was essential so that the rays would follow essentially parallel paths. At the same time, a gamma ray beam of small cross section was desired in order to be able to use foil banks of reasonable thickness. Further, it was desirable that a high counting rate be obtained so that a small percentage variation in the counting rate would produce a relatively large total variation. The larger the total variation, the easier this variation would be to detect, and the higher the counting rate, the less would be the time required to obtain statistically accurate data.

With the source strength a fixed quantity, a balance had to be reached between the degree of collimation and the counting rate obtained. The arrangement decided upon was a total collimated length of 16 inches and a gamma ray beam 3/16 inch in diameter upon leaving the last collimator block. Using a value of 1% for the counter efficiency and assuming that all gammas leaving the collimators struck the counter tube, this arrangement gave a calculated counting rate of 38 counts per minute. A counting time of 30 minutes was therefore required to produce a standard deviation on the order of ± 1 count per minute. A larger opening in the collimators would have produced a higher counting rate, but it would also have decreased the amount of collimation obtained. Correspondingly, a higher counting rate could have been obtained by shortening the collimated length, but this would also have decreased the collimation.

While it is felt that the arrangement used was the best possible for the source used, it is considered that the most desirable arrangement would be where the gamma ray beam was collimated to about 1/8 inch in diameter over a distance of about 3 feet and could produce a counting rate on the order of 100 counts per minute. Such an arrangement should give better experimental results. However, it would require a source of Co^{60} on the order of 3-4 millicuries, or about 30-40 times as large as the source actually used. While precautions would have to be taken in handling such a source, it is felt that an arrangement as described would allow the collection of more valid data over a shorter period of time.

The foil banks were used in two positions during the experimental work. In the first position, the plane formed by the leading edges of the foils in the foil bank was made to coincide with a plane containing the swivel axis of the transit and to be perpendicular to the central axis of the collimated beam of gamma rays. It was further centered so that the central axis of the collimated beam struck the face of the foil bank approximately mid-way between the sides of the bank. In this position, the face of the foil bank was 20 inches from the source and 4 inches from the last collimator block.

In the second position, the foil bank was moved to the edge of the glass compass face of the transit, so that it was 17 1/2 inches from the source and 1 1/2 inches from the last collimator block. In this position it was also placed so that the face of the foil bank was perpendicular to the central axis of the collimated beam and the beam struck the face of the bank mid-way between the sides. This position was used to determine what effect was obtained when the collimated beam had not had much opportunity to spread after leaving the collimators.

The counter tube was placed at a fixed distance of 5 inches from the swivel axis of the transit. It was so arranged that when the tube was lined up with zero deflection, an extension of the axis of the tube passed through the swivel axis of the transit and coincided with the axis of the gamma ray beam.

As the diameter of the outermost portion of the transit body measured 7 3/4 inches, the minimum distances between the last collimator and the face of the foils and between the transit swivel axis and the window of the counter tube could not have been appreciably decreased below the distances given above, 1 1/2 inches and 5 inches respectively.

B. Testing Procedure

Testing of the reflective properties of the foils was accomplished in two steps. The counter tube was first placed with zero deflection, so that it was in line with the source and collimator holes. With the tube in this position, the foil bank was rotated through various angles in both the clockwise and counterclockwise directions in an attempt to determine the optimum position for deflection of the maximum number of gamma rays. Measurements of the counting rate were taken at 5 minute variations in angle. This procedure was followed with the idea that a drop in the observed counting rate would indicate a deflection of a higher percentage of the gamma rays. The small angular variation between successive measurements was required because of the very small critical angles involved.

After a foil setting was determined which gave the maximum decrease in the counting rate, the foil was left at this position while the counter tube was rotated through various angles in both the clockwise and counterclockwise directions. Measurements were taken to determine the counting rates at these angles. An increase in the counting rate over the background count indicated that gamma rays were being deflected from the collimated beam in the direction of the counter tube.

All foils were placed to deflect the beam to the right as it traveled from the source to the counter. Only a single bank of foils was used rather than the proposed double bank, because, with the collimated beam of gamma rays, it was believed to be possible to set the angle of incidence so that the majority of the gammas would be deflected by the single bank.

Foil sets number 3, 4 and 5 each consisted of four essentially identical foil banks formed by wrapping the foil around a cylinder and then cutting the roll of foil at the quarter points. As used, each set was

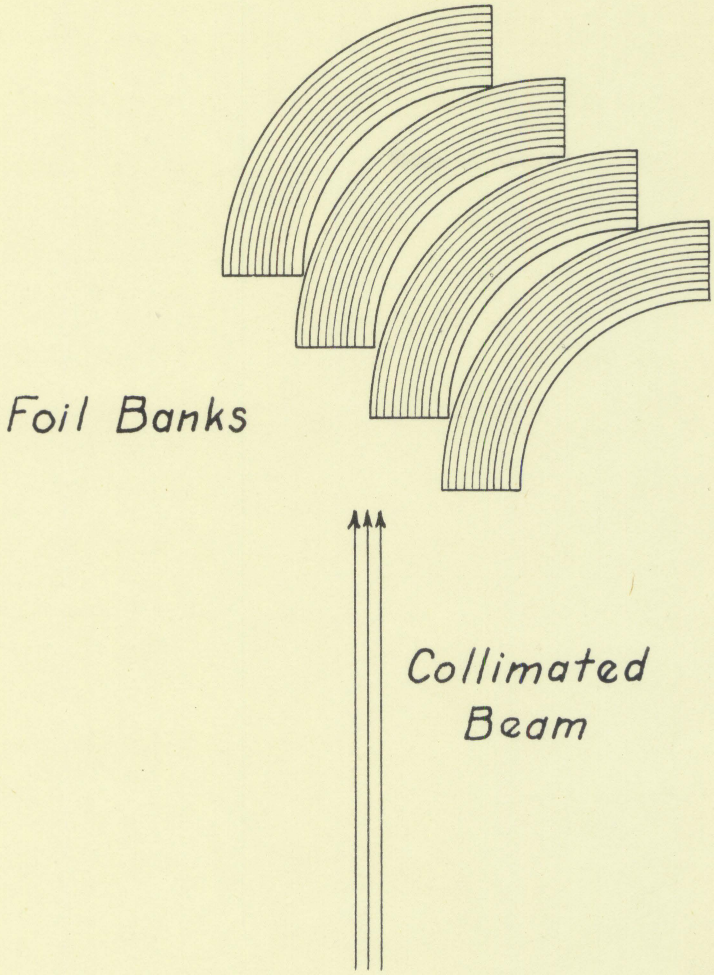


Fig. 5. Arrangement of foil bank set

arranged so that the foil banks were in echelon to the left rear, as is shown schematically in Figure 5. The faces formed by the leading edges of each bank were parallel to each other and, with the foils in the zero position, parallel to a plane perpendicular to the collimated beam. The effective area presented by the face of the foil bank was thus increased by a factor of nearly four. The echeloning was necessary so that the planes of the faces of the individual foil banks would be parallel.

VI. RESULTS

It became readily apparent at the beginning of the experimental work that foils number 1 and number 2 were inadequate for the collection of valid data. Both foils were too small to be of any value, inasmuch as the widths of the areas presented by the faces of the foils to the gamma ray beam could intercept no more than about 50% of the gamma rays in the beam. Foil number 3, which had been prepared using alternate layers of aluminum foil and manifold paper, was large enough to intercept all of the gamma rays in the collimated beam. However, it was felt, based on the calculations of the critical spacing, that the alternate layers of paper, used as spacing, contributed nothing to the efficiency of the foil bank.

Thus, all data contained herein were collected with foil sets number 4 and number 5, at the settings specified under Procedure. An additional set of data was taken for foil set number 5 at the 20-inch source to foil distance after the position of the foil set had been changed.

Figure 6 is a curve of the counting rate versus the counter tube position, plotted from data obtained when no reflecting foil was used in the apparatus. The curve indicates the normal distribution of the counting rate when there was no deflection of the gamma ray beam.

In Figure 6, as well as in all other figures and tables in this section, data are listed and plotted as being taken at positive or negative angles. For the purpose of this report, a negative angle is defined

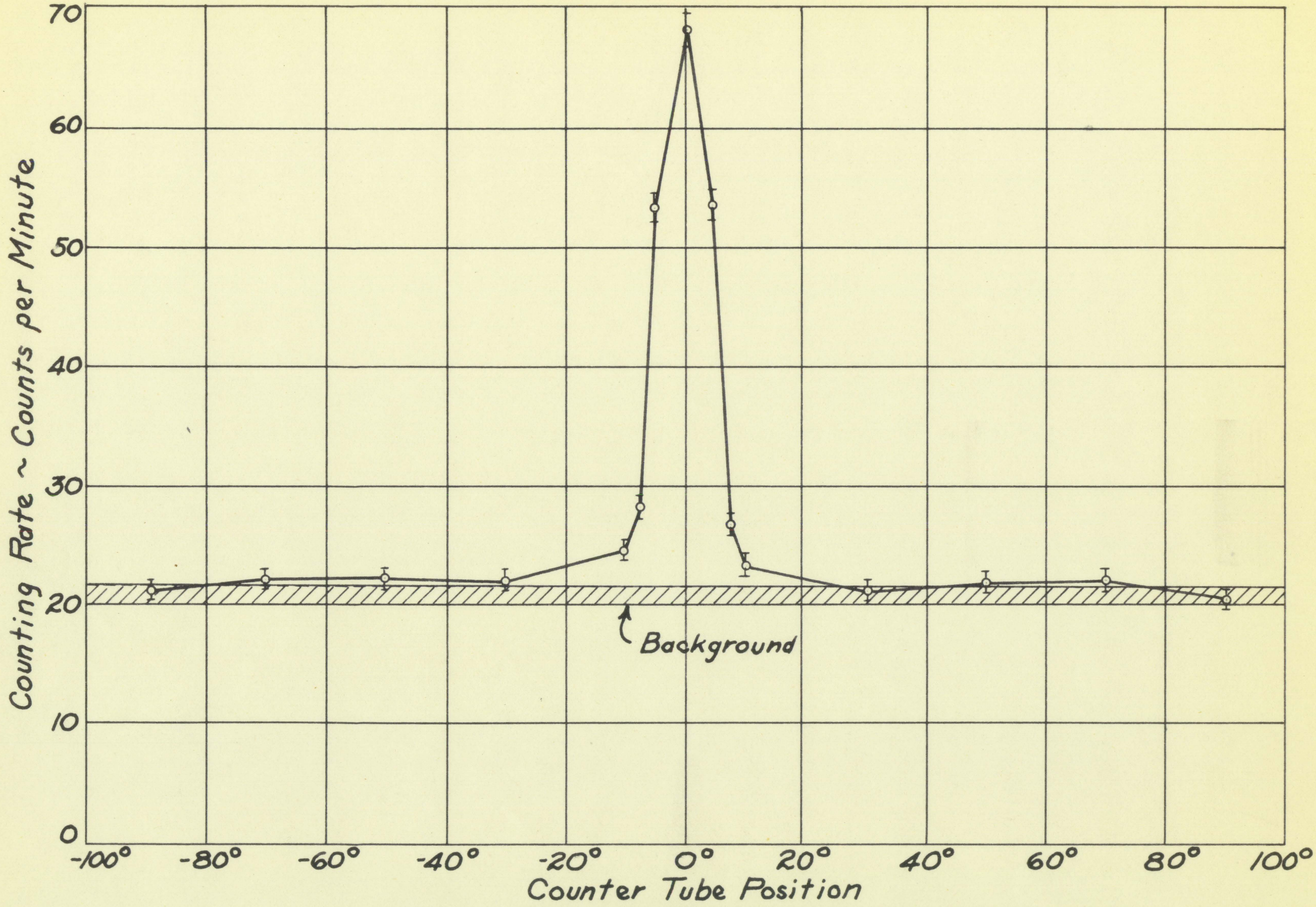


Fig. 6. Data obtained using no reflecting foil

as an angle taken in the clockwise direction when looking at the apparatus from the top, while a positive angle is defined as an angle taken in the counterclockwise direction. The zero position is defined as that position where the axis of the counter tube is coincident with an extension of the axes of the collimator holes. Angles of incidence on the reflecting foils are measured as defined above, relative to the zero position on the compass vernier.

Table 2 contains the data obtained using foil set number 4 at a source to foil distance of 20 inches and an angle of incidence on the foil bank of 0 degrees. Table 3 contains data obtained for the same foil set at a source to foil distance of 17 1/2 inches and an angle of incidence on the foil bank of 5 minutes. Curves of these sets of data are plotted in Figures 7 and 8 respectively.

Data obtained for foil set number 5 at a source to foil distance of 20 inches are tabulated in Tables 4 and 5. For Table 4, the angle of incidence of the gamma ray beam was 5 minutes, while for Table 5, the angle of incidence of the beam was 0 degrees. Curves of these sets of data are plotted in Figures 9 and 10 respectively.

Table 6 lists data obtained for foil set number 5 at a source to foil distance of 17 1/2 inches and an angle of incidence of the gamma ray beam of minus 10 minutes. These data are plotted in Figure 11.

The counting rates for the data were determined by taking the standard deviation as

$$\sigma = \frac{\sqrt{\text{Total count}}}{\text{Length of count (minutes)}}$$

Table 2. Data obtained using foil number 4 at a source to foil distance of 20 inches

Counter position	Length of count	Total counts	Counting rate counts per minute
- 90°	30 min	632	21.1 ± 0.8
- 85°	30 min	655	21.8 ± 0.9
- 80°	30 min	636	21.2 ± 0.8
- 75°	30 min	644	21.4 ± 0.8
- 70°	30 min	602	20.0 ± 0.8
- 60°	30 min	634	21.2 ± 0.8
- 40°	30 min	604	20.1 ± 0.8
- 20°	30 min	659	22.0 ± 0.9
- 10°	30 min	734	24.4 ± 0.9
- 5°	30 min	1580	52.6 ± 1.3
0°	30 min	1441	48.0 ± 1.3
5°	30 min	814	27.1 ± 1.0
10°	30 min	736	24.6 ± 0.9
30°	30 min	656	21.8 ± 0.9
50°	30 min	622	20.6 ± 0.8
70°	30 min	633	21.1 ± 0.8
90°	30 min	637	21.2 ± 0.8

Table 3. Data obtained using foil number 4 at a source to foil distance of 17 1/2 inches

Counter position	Length of count	Total counts	Counting rate counts per minute
- 100°	30 min	596	19.9 ± 0.8
- 95°	30 min	650	21.7 ± 0.8
- 90°	30 min	593	19.8 ± 0.8
- 85°	30 min	674	22.5 ± 0.9
- 80°	30 min	687	22.9 ± 0.9
- 70°	30 min	666	22.2 ± 0.9
- 60°	30 min	659	22.0 ± 0.9
- 40°	30 min	659	22.0 ± 0.9
- 20°	30 min	697	23.2 ± 0.9
- 10°	30 min	703	23.4 ± 0.9
- 5°	30 min	1991	66.4 ± 1.5
0°	30 min	1392	46.4 ± 1.2
5°	30 min	1573	52.4 ± 1.3
10°	30 min	949	31.6 ± 1.0
20°	30 min	783	26.1 ± 0.9
40°	30 min	642	21.4 ± 0.8
60°	30 min	671	22.2 ± 0.8
80°	30 min	685	22.8 ± 0.8
90°	30 min	639	21.3 ± 0.8

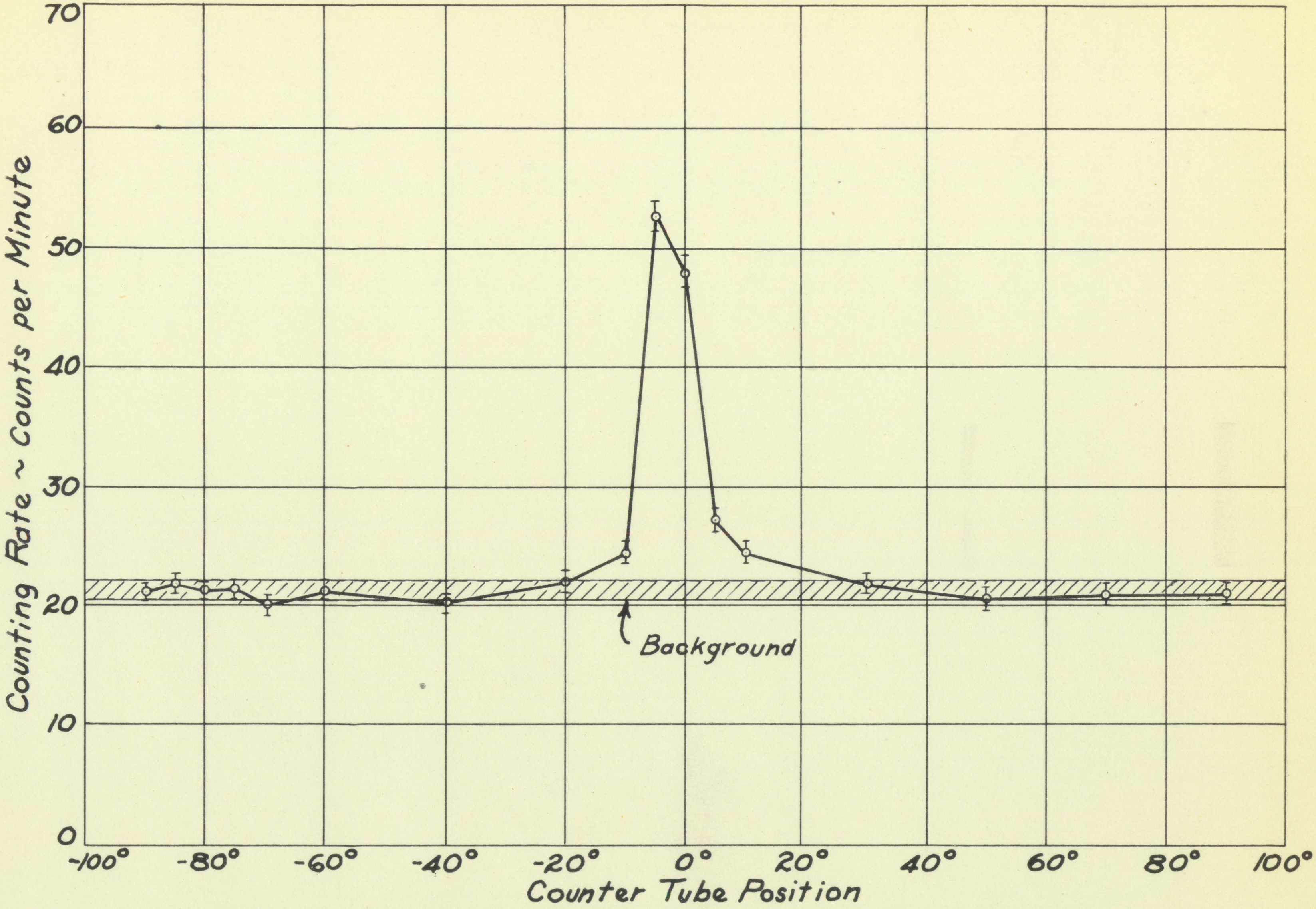


Fig. 7. Data obtained using foil number 4 at 20 inches from the source

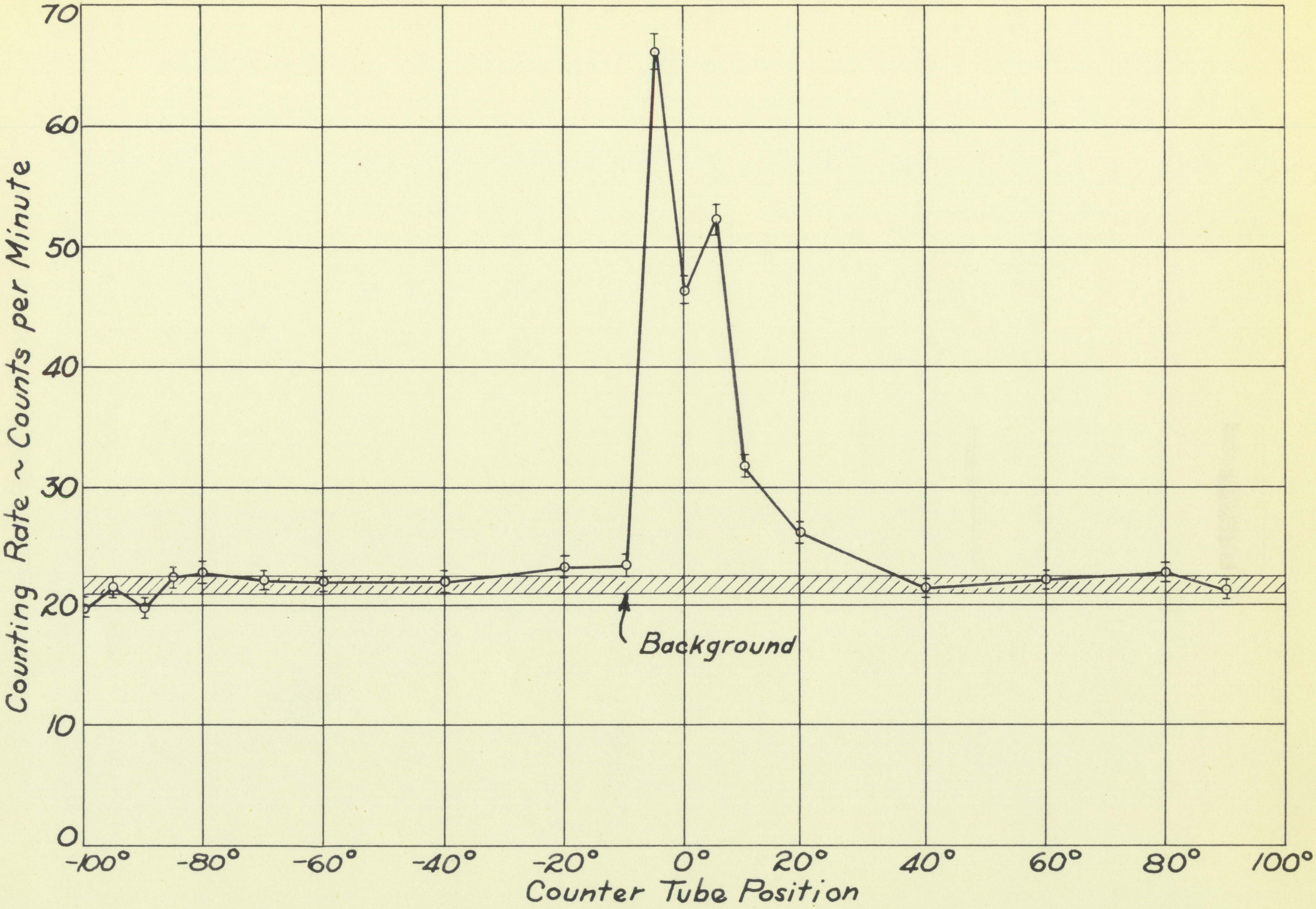


Fig. 8. Data obtained using foil number 4 at 17 1/2 inches from the source

Table 4. Data obtained using foil number 5 at a source to foil distance of 20 inches

Counter position	Length of count	Total counts	Counting rate counts per minute
- 90°	30 min	670	22.3 ± 0.9
- 85°	30 min	636	21.2 ± 0.8
- 80°	30 min	631	21.0 ± 0.8
- 75°	30 min	617	20.6 ± 0.8
- 70°	30 min	664	22.1 ± 0.9
- 60°	30 min	672	22.4 ± 0.9
- 40°	30 min	624	20.8 ± 0.8
- 20°	30 min	683	22.7 ± 0.9
- 10°	30 min	679	22.6 ± 0.9
- 5°	30 min	1973	65.8 ± 1.5
0°	30 min	1529	51.0 ± 1.3
5°	30 min	1971	65.7 ± 1.5
10°	30 min	700	23.3 ± 0.9
30°	30 min	621	20.7 ± 0.8
50°	30 min	644	21.5 ± 0.8
70°	30 min	587	19.6 ± 0.8
90°	30 min	622	20.7 ± 0.8

Table 5. Data obtained using foil number 5 at a source to foil distance of 20 inches

Counter position	Length of count	Total counts	Counting rate counts per minute
- 100°	30 min	600	20.0 ± 0.8
- 95°	30 min	607	20.2 ± 0.8
- 90°	30 min	670	22.3 ± 0.9
- 85°	30 min	615	20.5 ± 0.8
- 80°	30 min	641	21.4 ± 0.8
- 75°	30 min	686	22.9 ± 0.9
- 70°	30 min	627	20.9 ± 0.8
- 60°	30 min	652	21.7 ± 0.9
- 40°	30 min	657	21.9 ± 0.9
- 20°	30 min	651	21.7 ± 0.8
- 10°	30 min	695	23.2 ± 0.9
- 5°	30 min	1997	66.6 ± 1.5
0°	30 min	1500	50.0 ± 1.3
5°	30 min	1660	55.3 ± 1.4
10°	30 min	1384	46.1 ± 1.2
20°	30 min	694	21.1 ± 0.8
40°	30 min	686	22.9 ± 0.9
60°	30 min	603	20.1 ± 0.8
80°	30 min	587	19.6 ± 0.8
90°	30 min	574	19.1 ± 0.8

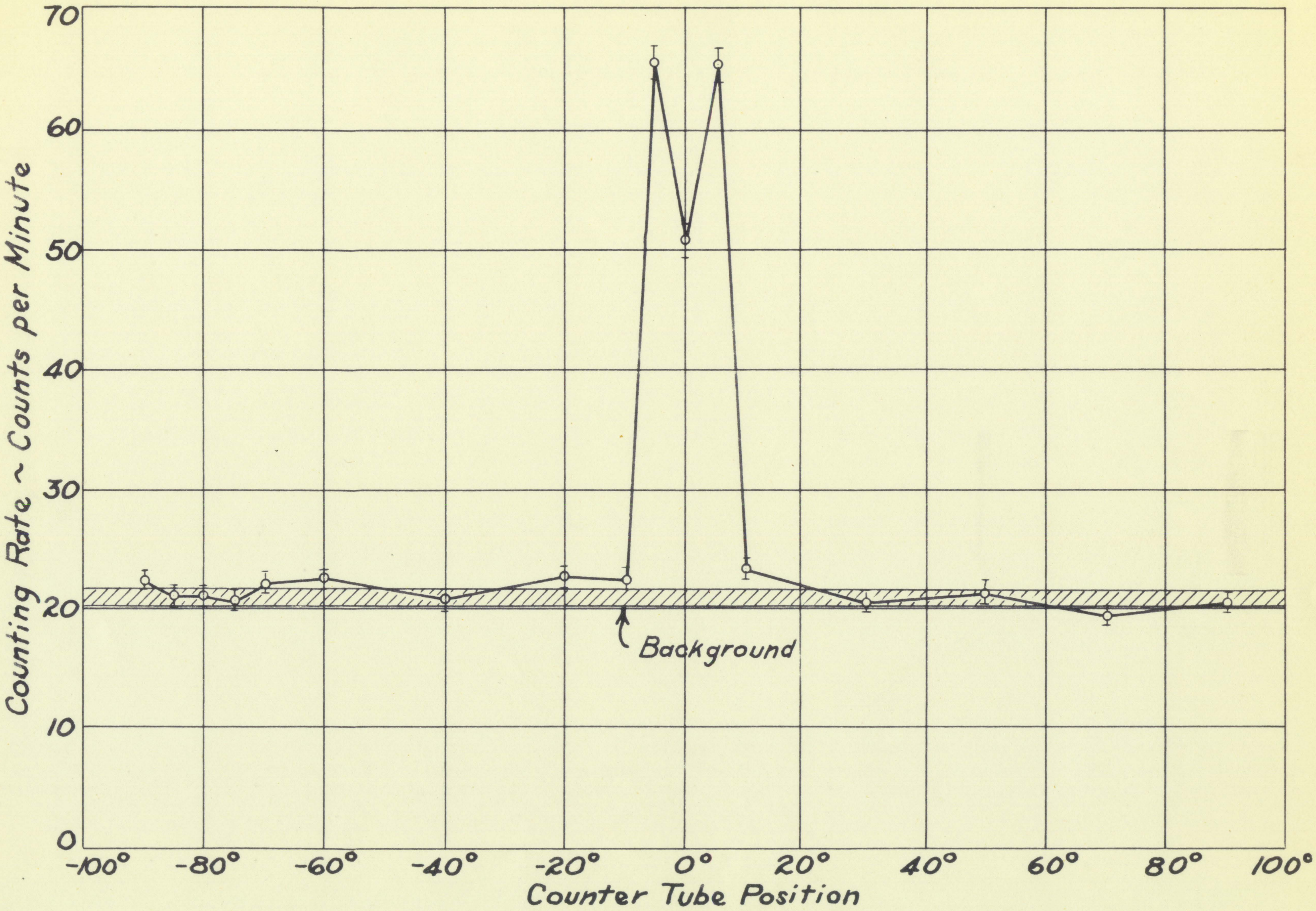


Fig. 9. Data obtained using foil number 5 at 20 inches from the source

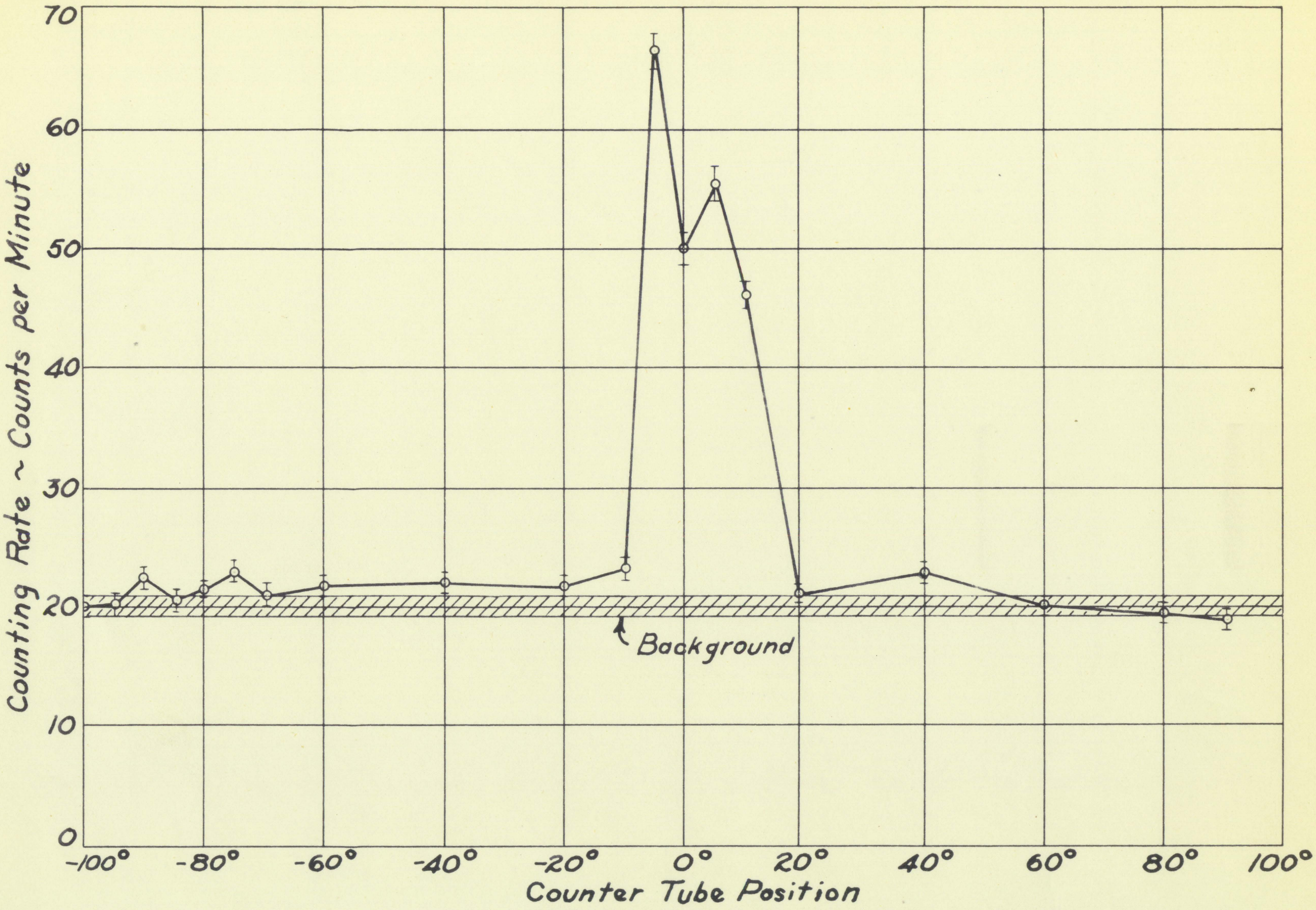


Fig. 10. Data obtained using foil number 5 at 20 inches from the source

Table 6. Data obtained using foil number 5 at a source to foil distance of 17 1/2 inches

Counter position	Length of count	Total counts	Counting rate counts per minute
- 100°	30 min	679	22.6 ± 0.9
- 95°	30 min	660	22.0 ± 0.9
- 90°	30 min	680	22.7 ± 0.9
- 85°	30 min	647	21.6 ± 0.8
- 80°	30 min	656	21.9 ± 0.9
- 60°	30 min	667	22.2 ± 0.9
- 40°	30 min	685	22.8 ± 0.9
- 20°	30 min	677	22.6 ± 0.9
- 10°	30 min	747	24.9 ± 0.9
- 5°	30 min	1590	53.0 ± 1.3
0°	30 min	1215	40.5 ± 1.2
5°	30 min	906	30.2 ± 1.0
10°	30 min	705	23.5 ± 0.9
30°	30 min	659	22.3 ± 0.9
50°	30 min	656	22.2 ± 0.9
70°	30 min	627	20.9 ± 0.8
90°	30 min	591	19.7 ± 0.8

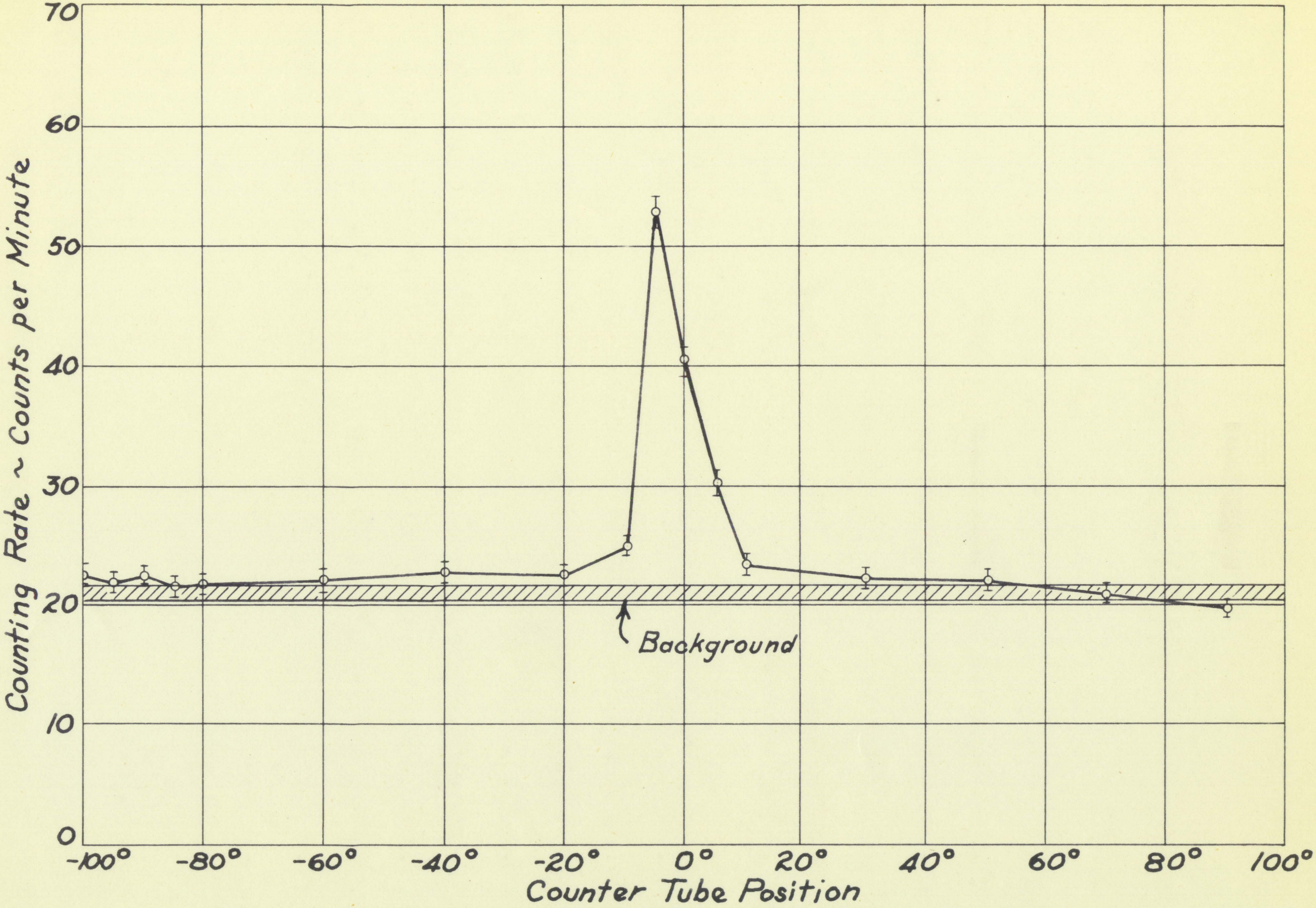


Fig. 11. Data obtained using foil number 5 at 17 1/2 inches from the source

Thus, the counting rate for a particular total count is given by

$$\text{Counting rate} = \frac{\text{Total count} \pm \sqrt{\text{Total count}}}{\text{Length of count (minutes)}}$$

The curves plotted in Figures 6 through 11 were not corrected for background activity. Instead, the measured counting rates were plotted. The curves as shown may be corrected for background activity by subtracting the value of the background, indicated by the horizontal band across the bottom portion of each curve, from the values of the individual points plotted for the curves. The data were plotted in this manner to obtain continuous curves, since some of the counting rates obtained fell below the background activity.

While the data for tables 2 through 6 were collected using specific angles of incidence of the collimated beam on the reflecting foils, these angles of incidence cannot be considered significant. The method of placement of the foil banks on the glass top of the compass was such that errors of the order of ± 2 degrees could have occurred. Thus, since the angles of incidence were measured in terms of minutes, there was essentially no reproducibility of a given foil position once the foil had been removed from the glass face of the compass.

VII. DISCUSSION OF RESULTS

The curve of Figure 6, plotted from data obtained with no reflecting foil in the apparatus, indicates that the activity from the gamma ray beam fell into a band approximately fifteen degrees wide centered on the zero position of the counter tube. This result is what was expected, inasmuch as calculations indicated that the collimated gamma ray beam covered a circular area about 0.3 inch in diameter at a distance of 25 inches from the source, or at the distance of the counter tube. The spread of the band was due to the diameter of the unshielded counter tube. A deflection of the counter tube of 5 degrees on either side of the zero position still allowed a fraction of the gamma rays in the collimated beam to strike the tube. The arrangement of the apparatus was purposely made this way in order to count as large a fraction of the gamma rays as possible at any particular deflection of the counter tube.

Had the foils been impermeable to the gamma rays, i.e., had all the gamma rays been deflected, then the peak in the counting rate curve observed in Figure 6 would have been translated to the left by about 80 to 100 degrees in the curves obtained using the foils. However, based on calculations of the maximum foil spacing, it was known that the foils could not be impermeable to the gamma rays. Thus, the total shift of the counting rate curve to the left was not expected. It was expected, however, that there would be some shift of the curves to the left and, perhaps, a small increase in the counting rates in the vicinity of minus 80 degrees to minus 100 degrees.

In each of the curves obtained, Figures 7 through 11, small increases in the counting rates were obtained somewhere in the interval from minus 100 degrees to minus 60 degrees. In Figures 7, 8 and 9, however, the increases were not large enough to be beyond the limits of statistical variation and, hence, these results cannot be considered significant. In addition, Figure 11, although showing an increase both at minus 90 degrees and minus 100 degrees as well as a small increase over the interval from minus 60 degrees to minus 20 degrees, is considered to show little more than a trend, since the values obtained with their standard deviations are only slightly more than could be expected from the standard deviation in the background activity.

Figure 10, however, shows increases in the counting rates at minus 90 degrees and minus 75 degrees as well as a general increases over the interval from minus 60 degrees to minus 20 degrees. These increases, particularly at minus 90 degrees and minus 75 degrees, are large enough to be taken as being definitely above any statistical variation. Hence, there is a definite indication that a portion of the gamma rays were totally deflected through angles up to 90 degrees.

In all curves, the majority of the gamma rays, as indicated by the counting rates, were counted in the vicinity of the zero position of the counter tube. In Figures 7 and 11, however, it is seen that the peaks in the counting rates were obtained at a minus 5 degrees, rather than at 0 degrees as was the case when no foil was used. Thus, it is apparent that the majority of the gamma rays underwent a small deflection in the direction predicted by the theory.

Figures 8 and 10, while showing peaks in the activity at a minus 5 degrees and hence indicating a small deflection of most of the gamma rays in this direction, also show smaller peaks at a plus 5 degrees. These results were not anticipated and the data were checked by additional counts to ascertain that they were valid. Additional counts gave similar results.

It is believed that the double-peak effect in the curves of Figures 8 and 10, as well as the curve of Figure 9, can be attributed to the shape of the collimated gamma ray beam. As the collimation was produced over a distance of 16 inches, the collimated beam was in the shape of a cone with a very large ratio of altitude to radius of base. Thus, the gamma rays were, in fact, not traveling in parallel paths upon leaving the collimator, but were traveling slightly divergent paths. Hence, it is possible that the gamma rays could be incident upon either the inner or outer surfaces of the individual foils. If a gamma ray were to strike the curved element on the outside surface of the curve at less than the critical angle, it would be deflected in the direction opposite of the direction anticipated for deflection to occur. Therefore, it is considered that the smaller peaks of Figures 8 and 10 were caused by slightly divergent gamma rays striking the reverse sides of the foils in the foil banks and being deflected in the counterclockwise direction. In Figure 9, the effect of the reverse deflection was relatively large, since the curve obtained indicates a symetrical distribution around the zero position.

In aluminum, the predominant process which effects an attenuation of gamma rays with energies in the range from 0.05 Mev to 15 Mev is

Compton scattering. The gammas from Co^{60}, with energies of 1.17 Mev and 1.33 Mev are well within this energy range. They have energies far enough above the lower limit of 0.05 Mev to make the contribution of the photoelectric effect rather negligible. At the same time, since the gammas have energies only slightly above the threshold energy of 1.02 Mev which is necessary for pair production to occur, the contribution of this effect to the attenuation of the gamma rays may also be neglected. Hence, any interaction of the gamma rays from the Co^{60} with the aluminum during this experimental work was caused primarily by Compton scattering.

A consideration of the effect that Compton scattering might have had on the observed results of the experimental runs leads to two observations:

1. If Compton scattering did occur, it would have been preferential scattering in the forward direction, but without preference as to the angle of scatter. In other words, no net increase in the activity should have been observed at any particular counter position due to the effect of Compton scattering.

2. If a gamma ray were scattered in the clockwise direction from the initial direction of the collimated beam, it would have to penetrate a greater thickness of aluminum before emerging from the foil bank than if it had been scattered in the counterclockwise direction. Hence, there would be a greater opportunity for secondary scattering to occur and, thus, less probability for continued travel in the direction of initial scatter.

It is considered, therefore, that the results obtained in the experimental work could not be attributed to any of the three processes normally associated with the interaction of gamma rays with matter. Hence, it follows that any deflection of the gamma rays from their original paths must have been the result of multiple reflections from the curved foils.

VIII. CONCLUSIONS

The following conclusions were drawn from the experimental results:

1. While aluminum is possibly not the material which is best suited for reflection of the gamma rays, the use of the aluminum in the foil banks produced indications of relatively large angle deflections of the gamma rays in the direction predicted by the theory.

2. While the gamma rays were not deflected through large angles approaching 90 degrees, except possibly in the case of Figure 10, the small deflections that did occur in the vicinity of the zero position for the counter tube indicate a possibility of accomplishing large angle deflection with the use of proper foil materials and adequate radii of curvature of the foils.

3. In view of the need for an improved type of gamma ray shield, the principle of reflective shielding is worthy of further study toward the development of a practical reflective type shield.

IX. RECOMMENDATIONS

A. Possible Solutions for Problems Encountered

It is felt that one of the major problems faced during the course of the experimental work was the lack of a strong source of radiation. While the source used was adequate to obtain data, it necessitated a rather poor collimation of the gamma ray beam and required rather long counting times in order to obtain statistically accurate data. Further, a small variation in the percentage deflection of the gamma rays was difficult to detect, where with a larger source there would have been a readily noticeable decrease in the number of total counts obtained. It is recommended that any future work in this field be accomplished with a source whose strength is on the order of several millicuries.

Aluminum foil was used throughout this experiment. It is entirely possible that the critical angle for reflection from the aluminum might be much smaller than that for other materials. Tests could, and should, be run using other materials to determine their applicability to the problem. From the data published by Doan, Table 1, it appears that copper might offer the best qualities of those materials tested, inasmuch as the critical angles appear to decrease at a slower rate with increasing energy of the X-rays. Therefore, the copper should have a larger critical angle than the other materials tested for the higher energies of radiation.

In part II B of this report, a proof was shown indicating the order of magnitude of the spacings required between foils for a critical angle of 12 minutes and a radius of curvature of 5 centimeters for the foils. A value of 3050 Å was obtained. The aluminum foil used in this experimental work was 0.00045 inches or 0.0011430 centimeters thick. This is equivalent to a thickness of 114,300 Å, or is greater than the maximum foil spacing by a factor of nearly 38. In order to have a foil spacing of the same order of magnitude as the foil thickness used, a foil bank with a radius of curvature of about 190 centimeters would be required. The foils used in this experiment obviously had radii of curvature much less than this amount. In addition, it is probable that the critical angle of aluminum for gammas of the energies used is considerably less than 12 minutes.

It is apparent that if the foil bank must have a radius of curvature of nearly 2 meters or more, then the thickness of the complete shield, which must have a minimum thickness of two foil banks, would be entirely excessive, particularly for use in a mobile unit. Two alternatives are possible to decrease the shield thickness, however. One possibility is to decrease the foil thickness. This alternative is not very desirable, due to the fabrication problems that would be encountered. The other possibility is that a material may be found which has a much larger critical angle for reflection of high energy gammas. Such a material might allow fabrication of a shield using reasonable thicknesses of foils and still maintain a small overall shield thickness.

B. Possible Courses of Action

It is felt that any further research along this line should be devoted primarily to a study of various materials to determine that material which has the best reflective properties. Larger critical angles appear to offer the best means of solving the problems involving the size of the shield.

C. Possible Applications

The shield as originally envisaged by Proell was to be used to protect the crew of a rocket ship from the radiation produced by its nuclear power propulsion system. Such a shield would also be applicable to aircraft and possibly to submarines or surface vessels where radiation escaping through the sides of the craft would pose no problem. The shield, in this case, would consist of a double bank of the foils which would merely deflect the gamma rays either to one side or the other. Once deflected, the rays would not affect the personnel involved except for that small portion of the rays which might undergo small angle scattering and be directed back toward the vessel.

A shield of this nature would have rather small application except in these special cases, but with a variation in its construction it should also be applicable to surround a reactor or other radioactive source of gamma radiation. If the individual foils are made to be initially perpendicular to a cylindrical surface rather than a plane surface, then the foil bank should close on itself. This is equivalent to taking a bank of foils which are perpendicular to a plane surface and bending the plane into a cylinder. This foil bank would then produce a 90 degree deflection of the incident gamma rays. The bank could then be enclosed with a thin cylindrical shell so that upon the emergence of the gamma rays from the bank they would strike the shell. As the radius of curvature of the shell would have to be larger than the radius of curvature of the foils, from geometrical considerations, then after being deflected 90 degrees by the foils, the gamma rays would strike the shell at less than the critical angle and start a series of reflections around the inner surface of the shell. As the shell would close upon itself, the gammas would continue the reflections and would not penetrate the shell. The effect of this should be advantageous from a power reactor point of view, because all of the energy of the gamma rays would be contained within the reactor unit and would add to the total energy available. The entire shield, of course, would have to consist of at least two such banks of foils, curved in opposite directions and each with its own shell surrounding the bank.

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XI. ACKNOWLEDGMENTS

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