OPTIMUM THICKNESS OF PLASTIC SCINTILLATORS

by

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ABSTRACT

A thin plastic scintillation detector can be made to demonstrate total absorption of incident gamma ray energy by laminating it with lead. The purpose of this thesis is to attempt to determine the thickness of plastic that will give an appreciable increase in the photoelectric peak and at the same time have a reasonable resolution, so as to give a good representation of the incident gamma energy spectrum.

A series of experiments was conducted with various thicknesses of plastic laminated with 0.0304 cm of lead using gamma sources between 0.05 mev and 3.0 mev. It was found that, as the plastic thickness was increased, the count rate increased but the resolution of the detector became worse. It was determined that a plastic 1.270 cm thick had the best compromise between total count and resolution, but none of the plastics tested were able to resolve the two peaks in the cobalt 60 spectrum. The efficiency of the optimum detector for several gamma energies was also calculated by a Monte Carlo Computer computation. The efficiency varied from 86.6% for the low energy gammas to 17.3% for the higher

energies. An energy absorption ratio for the plastic was also computed and it varied from 7.7% to 25.9%.

The laminated lead-plastic scintillation detector for gamma detection appears to have a limited value, but the computer calculation offers a method of determining the energy absorbed in a small sample of organic material since plastic has a tissue-equivalent response to gamma radiation.

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TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

The development of plastic materials for use in scintillation detectors has opened the way for many advances in radiation detection equipment. Plastic can be procured in a wide variety of sizes at moderate cost and can easily be machined into any desired shape. It is also non-hygroscopic, and does not have to be permanently encased to protect it from moisture. The only requirement for a cover is for light tightness. Since much thinner covers can be used, beta and alpha counting are routinely performed using plastic detectors. The use of plastics for gamma detection has come in for much study lately, primarily because a plastic detector has an almost air-equivalent response to gamma radiation over a wide energy range. The fact that plastic detectors are essentially tissue-equivalent in their response opens interesting possibilities for use in dosimetry measurements.

Even though plastic offers many advantages over liquid or the commonly used sodium iodide detectors, it has one very big disadvantage as a detector. This disadvantage results from its inability to demonstrate total absorption of gamma ray energy. Since plastic is made up primarily of hydrocarbons, it has a very low atomic number. The absorption coefficient for the photoelectric effect (which is a total absorption process) varies as Z^2, where Z is the atomic number of the material concerned. Thus plastic, with its low Z number, will have small photoelectric coefficients. This difficulty can be overcome by using a plastic of sufficient size so that multiple compton scatterings can occur and cause total absorption of the energy of the incident photon. A second possibility is to load the plastic with some high Z material such as gold, lead or uranium. The use of these materials will increase the probability of having a photoelectric absorption and make possible the demonstration of total absorption of the gamma ray energy.

Cline (1)* has shown that a thin plastic slab detector laminated with lead foil is responsive to incident gamma radiation. He found that, while he could detect a photoelectric peak in the gamma spectrum obtained with this detector, the increase in the count over the compton background was insignificant.

The purpose of this thesis is to investigate the possibility of improving the spectrum obtained from a laminated lead-plastic scintillation detector by varying the

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*See list of references.

thickness of the plastic crystal and thus determine an optimum thickness of plastic to use. The efficiency of the optimum detector will then be determined by a stochastic technique for several incident photon energies. The response of the detector will be analyzed to determine the possible application of the computer technique to the general problem of determining the energy absorbed in small samples of organic material.

CHAPTER 2

THE SCINTILLATION PROCESS AND THE DETECTOR

2.1 The Scintillation Process

There are many types of interactions that can take place as an incident photon passes through matter, but most of these occur at very high or very low incident photon energies. In this study the energy of the incident photon will be restricted to the limits of 0.05 mev to 3.0 mev. This will encompass most of the gamma rays emitted by the radio-active elements. Accordingly, only three types of interactions will be considered. These are the compton effect, pair production and the photoelectric effect.

The photoelectric effect, as was mentioned previously, involves the total absorption of the energy of the incident photon. The photon interacts with the target atom, and one of the orbital electrons is ejected with an energy equal to the energy of the incoming photon less the binding energy of the electron. This effect takes place at photon energies of 0.1 mev or less in most low and medium Z number materials. The binding energy of the electron is very small, so the ejected electron has essentially all the energy of the incident photon.

Pair production occurs only when the incident gamma has an energy in excess of 2 m_0c^2, and results in the formation of an electron-positron pair when the photon interacts with the nucleus of the target atom. In this interaction the photon is totally absorbed in the formation of the pair. The positron is soon annihilated by combining with an electron to produce two photons of equal energy. The electron and positron each receive one-half of the energy of the incident photon over 1.02 mev so the total energy absorbed in the scintillator varies from one-half of the incident photon energy to all of it, if both the secondary photons are totally absorbed in the material.

In the compton effect, the photon interacts with the atomic electrons of the target atoms, resulting in a scattered electron and a scattered secondary photon. The electron will be absorbed in the scintillator; and, if the secondary photon suffers enough interactions of its own to be totally absorbed, this type of interaction can also demonstrate the total absorption of the incident gamma energy. To insure that the secondary photon is completely absorbed, the crystal must be of sufficient size so that many compton scatterings are possible before the secondary photon escapes from the crystal.

It can be seen that each of the above processes results in the formation of at least one electron. It is this electron that loses its energy in the detector and results in a count in the analyzer. The electron gives up its energy as it passes through the material either by ionization or excitation of the atoms of the material through which it is passing. Most of the detector systems in use today use the ionization collection principle, where the amount of ionization produced in the material is recorded. This is usually done by counting the number of ion pairs produced in the material per unit time. However, the excitation principle can also be used to detect radiation. In this process a material is used which has the ability to absorb energy from the particle and re-emit it in the form of light photons or scintillations. These materials are called phosphers. In a phospher, the number of light photons produced is proportional to the energy of the electron, if it is assumed that the electron gives up all its energy in passing through the material (2). To detect and measure these light photons, a photomultiplier tube is used. The tube detects the light flashes, converts them to electrical energy which is amplified and transmitted as electrical pulses to the counting equipment.

Even though the total energy absorbed by the scintillation material from a compton and photoelectric interaction is the same, the response of the detector to these effects is not. This is due to the fact that we assume that the photoelectron is totally absorbed in the detector, while the electron receives only a part of the energy from a compton scattering. Thus the response of the detector will be less for a compton than a photoelectric interaction. Therefore the total number of light flashes or scintillations is proportional to the energy absorbed in the detector and not to the energy incident on it.

2.2 The Detector

The detector used to measure the response of various thicknesses of plastic is shown in Figure 2.1. The detector is the Nuclear-Chicago DS-100 Exposed Crystal Scintillation Detector using a Basic DS-5 probe. This probe is the Dumont 6292 photomultiplier tube with a built-in preamplifier and covered with a mu-metal shield to minimize the formation of secondary electrons and degraded photons in the casing. To this probe a Pilot B plastic scintillator was optically coupled to the photomultiplier tube using Dow-Corning stop-cock grease. The plastic was completely (except for the end coupled to the photomultiplier tube) wrapped in aluminum foil to improve the light collection. Lead foils of varying thickness were placed between the plastic and the source to attempt to produce total absorption of the incident photon energy. The plastic and lead detector was covered with an aluminum can 0.159 cm thick. This can serves two purposes. First, it provides a light-tight cover for the detector and photomultiplier tube; and secondly, it provides a means of

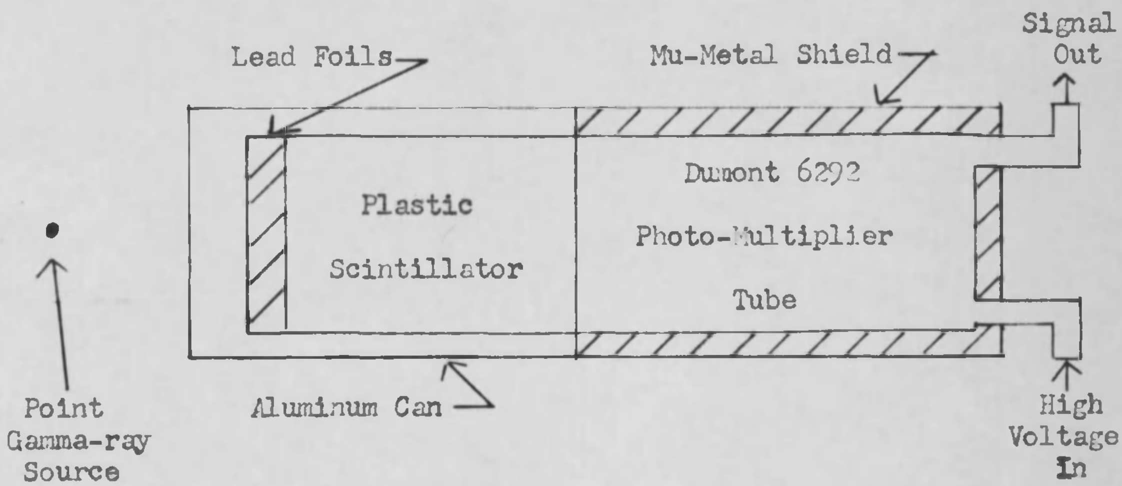


Figure 2.1 -A Diagram Showing the Experimental Set-up of the Lead-Plastic Laminated Scintillation Detector to Determine the Optimum Thickness of the Plastic Crystal.

attenuating the beta particles that normally accompany any gamma emission from a radiation source. These beta particles would affect the detector the same as the electron produced by the interaction of the gamma ray with matter. Since the purpose is to study the measurement of gamma radiation, it is most important that these beta particles be eliminated from the system. However, this aluminum can does produce a background of compton electrons from the interaction of the photons with the aluminum as they pass through the can. The can is relatively thin, and the probability of the photon passing through it without interaction is greater than 0.90 for the energy range specified above. Therefore this background will be a small fraction of the total count in the spectrum.

The output signal from the detector is fed to a two-hundred channel Pulse Height Analyzer Model 34-2 made by the Radiation Instrument Development Laboratory. This instrument has a very stable High Voltage Power Supply that was used to drive the detector system. The analyzer provides an immediate display of the spectrum on an oscilloscope as well as a printed record of the number of counts absorbed per channel. The printed record can then be plotted on graph paper to represent the gamma spectrum obtained from the detector.

The next chapter will describe the experiments that were conducted to determine the optimum thickness of plastic, and the results obtained from them.

CHAPTER 3

THE EXPERIMENT

3.1 General

In attempting to determine an optimum thickness of plastic to be used in a Gamma Scintillation Detector, the following thicknesses of plastics were used: 0.159 cm, 0.315 cm, 0.635 cm, 1.270 cm, 2.540 cm and 5.080 cm. The plastics were in the shape of a right circular cylinder and all had a diameter of 4.450 cm. Lead foils were chosen to laminate the detector because lead has a high Z number, is cheap and very easily obtained, and can be rolled into any shape desired. The foils used here were 4.450 cm in diameter and 0.0152 cm thick. They were used in cascade to obtain the thickness of foil desired.

To compare the detector over the energy range specified previously, three sources were chosen. These were Cobalt 60, which has two gammas of 1.17 and 1.33 mev; Cesium 137 which emits a single gamma of 0.662 mev; and Cerium 141 which decays by emitting a single gamma of 0.145 mev. The source was placed a distance of 0.635 cm from the face of the aluminum can on the axis of the detector.

The detector was set up as shown in Figure 2.1, and operated without a source for a certain period of time to obtain a background count for the detector and the room where the detector was operated. This background count was stored in the memory of the analyzer, and a gamma source was then counted for the same period of time. While the source was being counted, the background was automatically subtracted from the spectrum. By using the set-up shown in Figure 2.1 where the source is in the open a distance from the detector, there is very little backscattering of gamma rays to the detector. Since the background is removed, almost a pure spectrum of the gamma source being counted is left. It should be mentioned that a High Voltage setting of 1450 volts was used on the detector throughout all the experiments.

3.2 Effect of Lead on the Spectrum

Prior to varying the thickness of plastic, the effect of various thicknesses of lead foils on the spectrum was studied. Figure 3.1 shows the results of adding lead to a 1.270 cm thick plastic detector. It was found that adding a single foil resulted in very little change in the spectrum; but by adding two foils a definite photopeak appeared, indicating total absorption of the photon's energy. As more lead foils were added, the peak shifted toward the lower energy region and more counts appeared in the valley: until, with the use of eight foils, the spectrum very closely resembled the spectrum obtained with no lead.

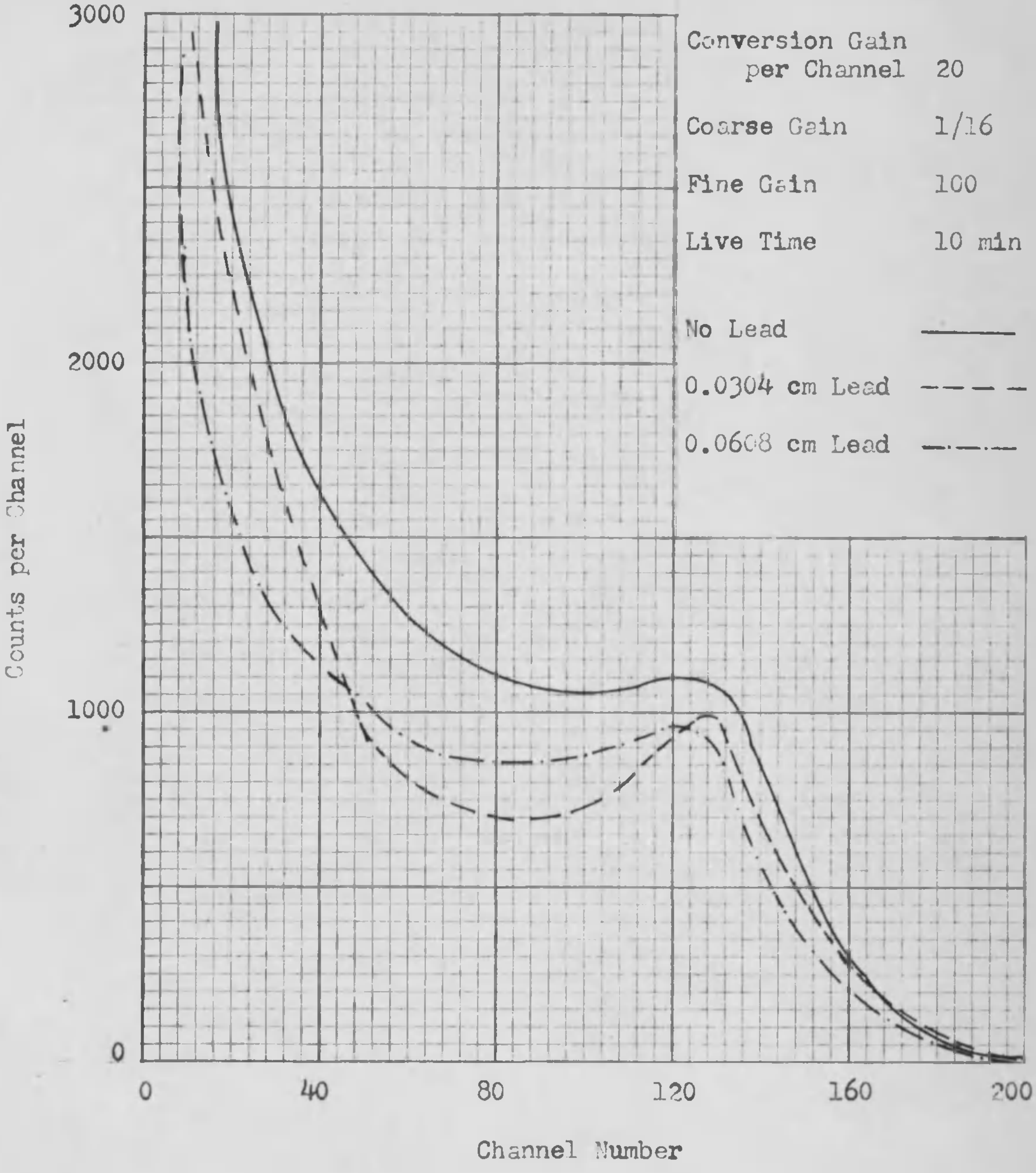


Figure 3.1 -Variation of the Cobalt 60 Gamma-ray Spectrum Caused by Adding Lead Foils to the Plastic Scintillator.

The spectrum with eight foils was shifted slightly below the spectrum with no lead added. The same type of results was obtained for all source and plastic combinations, except that there was little difference in the spectrum using one and two foils for the Ce 141 source. For uniformity, it was decided to use two foils for the rest of the experiment.

The reason for the small change in the spectrum when a single foil is added to the plastic appears to be due to the fact that the lead foil is so thin that most of the gamma rays are passing through without experiencing any interactions.

On the other hand, as the foil becomes thicker, more photons do have interactions in the lead, but the interactions are distributed throughout the foil. The electrons lose much of their energy traveling through the lead to reach the plastic, and thus appear at lower energies in the spectrum. This effect appears as counts in the valley. The range of electrons in lead can be calculated from (3):

$$Rn\ (cm) = 0.03625\ E^{(1.265-0.0954\ \ln E)} \qquad (3.1)$$

where E is the electron energy in mev. Using this equation the maximum range for electrons of the sources used are: Ce 141 (0.0125 cm), Cs137 (0.165 cm), and Co 60 (0.446 cm). From these ranges, it can be seen that very few of the electrons from a Cerium source will get through the lead without being totally absorbed. The electrons from the two other sources will lose much of their energy in the lead but will still produce a photopeak.

From Figure 3.1 we conclude that the use of two lead foils will give the best photopeak in the spectrum for all thicknesses of plastic and for all the sources. Hence in all the rest of the experiments, 0.0304 cm of lead foil was used on the plastic being tested.

3.3 Effect of Plastic Thickness

The next step was to vary the thickness of plastic used in the detector, and observe the change in the spectrum. It became immediately apparent that the thickness of the plastic had a direct effect on the total count obtained from a given source. The greater thickness of plastic present increases the probability of having an interaction between the photon and the material, and also increases the probability of the secondary photons having multiple interactions in the detector. The three sources were tested with various thicknesses of plastic and all showed a steady increase in the total count as the thickness of the plastic was increased. Figures 3.2, 3.3, and 3.4 show the results of increasing the plastic thickness from 0.635 cm to 2.540 cm for each of the three sources. It can be seen that in each case, doubling the thickness of the plastic results in the counts in the photopeak more than doubling. The total count in the

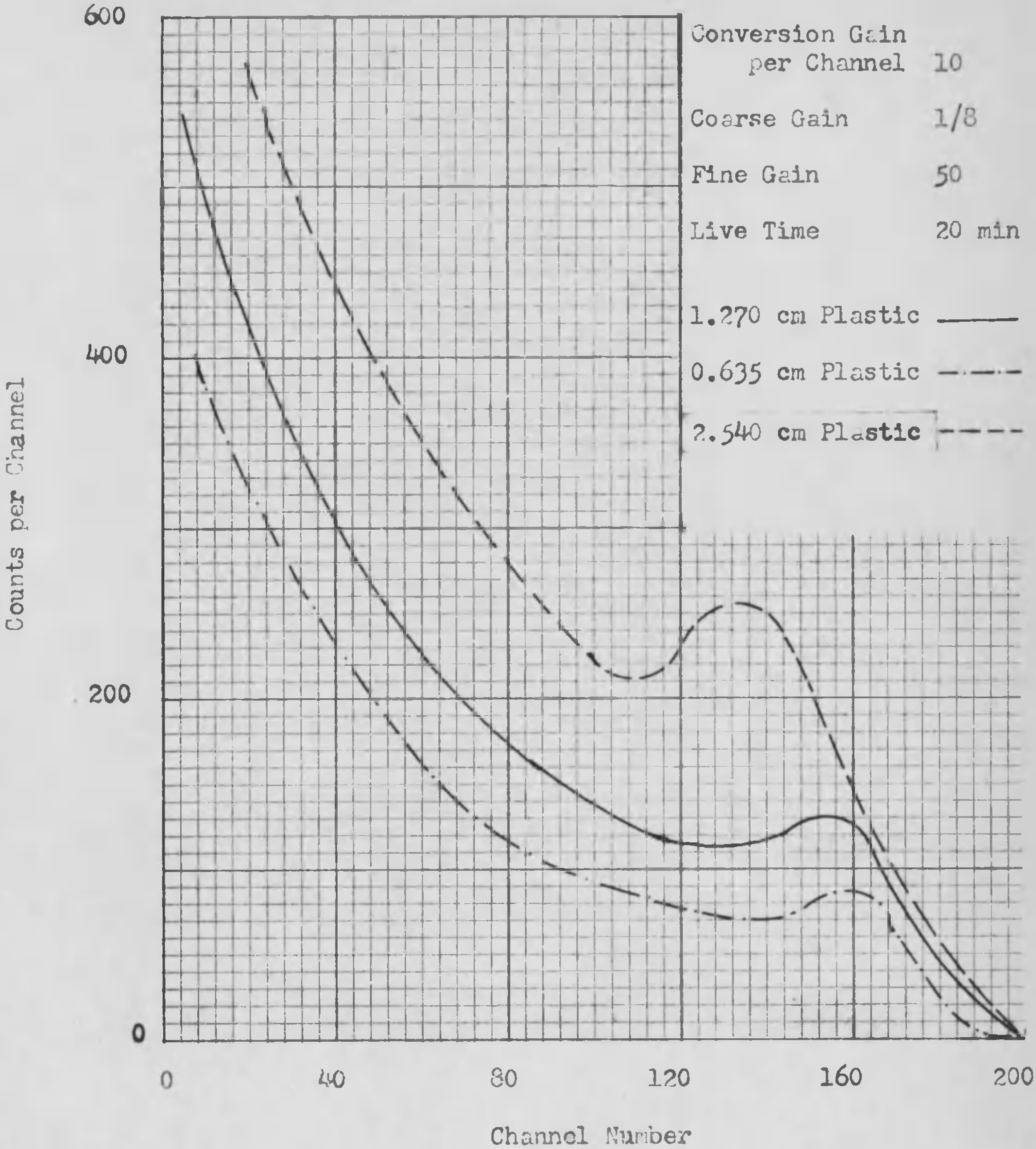


Figure 3.2 -Variation of the Ce 141 Gamma-ray Spectrum Caused by Changing the Thickness of Plastic Scintillator.

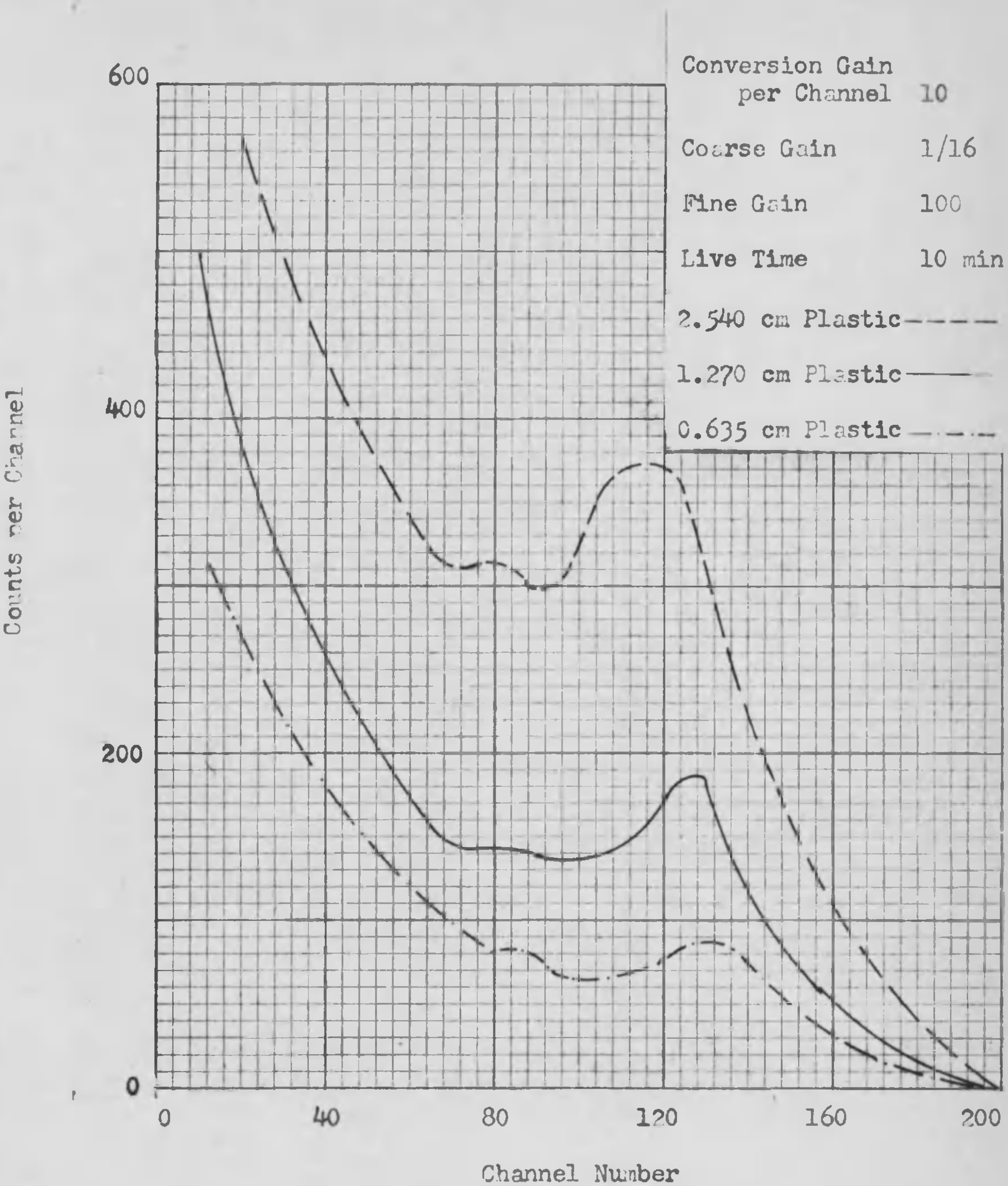


Figure 3.3 -Variation of the Cs 137 Gamma-ray Spectrum Caused by Changing the Thickness of Plastic Scintillator.

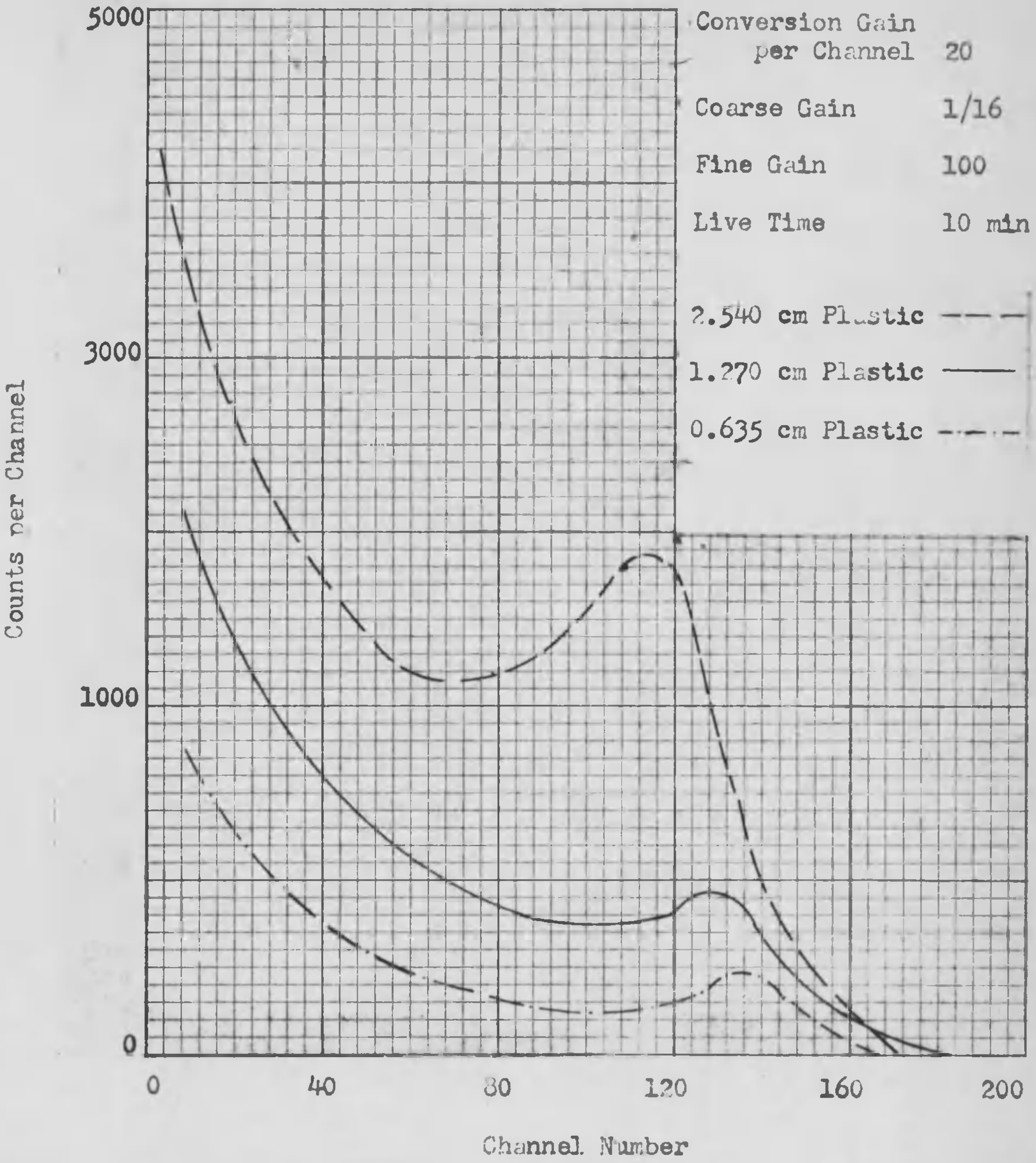


Figure 3.4 -Variation of the Co 60 Gamma-ray Spectrum Caused by Changing the Thickness of Plastic Scintillator.

spectrum increases more than three-fold in all cases. In each case the photopeak seems to shift to the left by as much as twenty channels as the detector thickness is increased.

Obviously it is desired to use the detector that absorbs the most energy from the photon, but it must also give a true representation of the energy distribution from the photon. One measure of this accuracy of representation is the resolution of the detector. Resolution is defined as the full width of the photopeak as measured at one-half the maximum count rate divided by the pulse height at the peak (4). Thus, resolution is a measure of the degree of broadening of the photopeak. The broadening of the photopeak is due to statistical variation of the energies of the relatively small number of electrons in the photopeak. It may also be said that resolution is a measure of a detector's ability to distinguish photopeaks close together. Experience has shown that, if a detector has a resolution of 12% or less, it is considered to be a good detector. The definition of resolution may be written as

$$\text{Res} = \frac{W_{\frac{1}{2}}}{C_m} \tag{3.2}$$

where $W_{\frac{1}{2}}$ is the width of the photopeak at one-half the maximum count rate expressed in number of channels, and C_m is the channel number at which the maximum point of the photopeak occurs. If a baseline bias is applied to each of the spectrums to eliminate most of the Compton background in the spectrum, the resolution of the spectrums shown in Figures 3.2, 3.3, and 3.4 can be calculated. The results are shown in Table I, and also in Figure 3.5. It can be seen that in no case is the resolution of the detector 12% or less, but for Cs 137, it is approached. For all three sources, the lead-plastic combination that has the best resolution is the 1.270 cm plastic detector, with 0.0304 cm of lead.

It appears that the thinner plastic allows many of the incident photons to pass through without any type of interaction. This results in a low count rate and hence, the few photoelectrons in the photopeak have very widely spaced energies. This results in a broad peak and low resolution. On the other hand, the thicker plastics have more interactions taking place including the absorption of many more secondary photons. Since these scattered photons are of all energies, many additional absorptions take place at energies near photopeak energy. Most of the gamma interactions take place in the part of the detector nearest the source. To show this, a 1.270 cm detector with an opaque shield in it a distance of 0.635 cm from the front face was used. The spectrum obtained from this detector is compared with the spectrum from 1.270 cm and 0.635 cm plastics.

Table I: Resolution of Detectors

Gamma Source & Detector	Channel Width at Half Maximum Count ($W_{\frac{1}{2}}$)	Channel No. at Maximum Point (C_m)	Resolution
Ce 141			
2.540 cm	27	137	0.199
1.270 cm	23	150	0.153
0.635 cm	26	160	0.162
Cs 137			
2.540 cm	22	117	0.188
1.270 cm	16	128	0.125
0.635 cm	18	130	0.144
Co 60			
2.540 cm	21	116	0.181
1.270 cm	18	132	0.136
0.635 cm	22	143	0.156

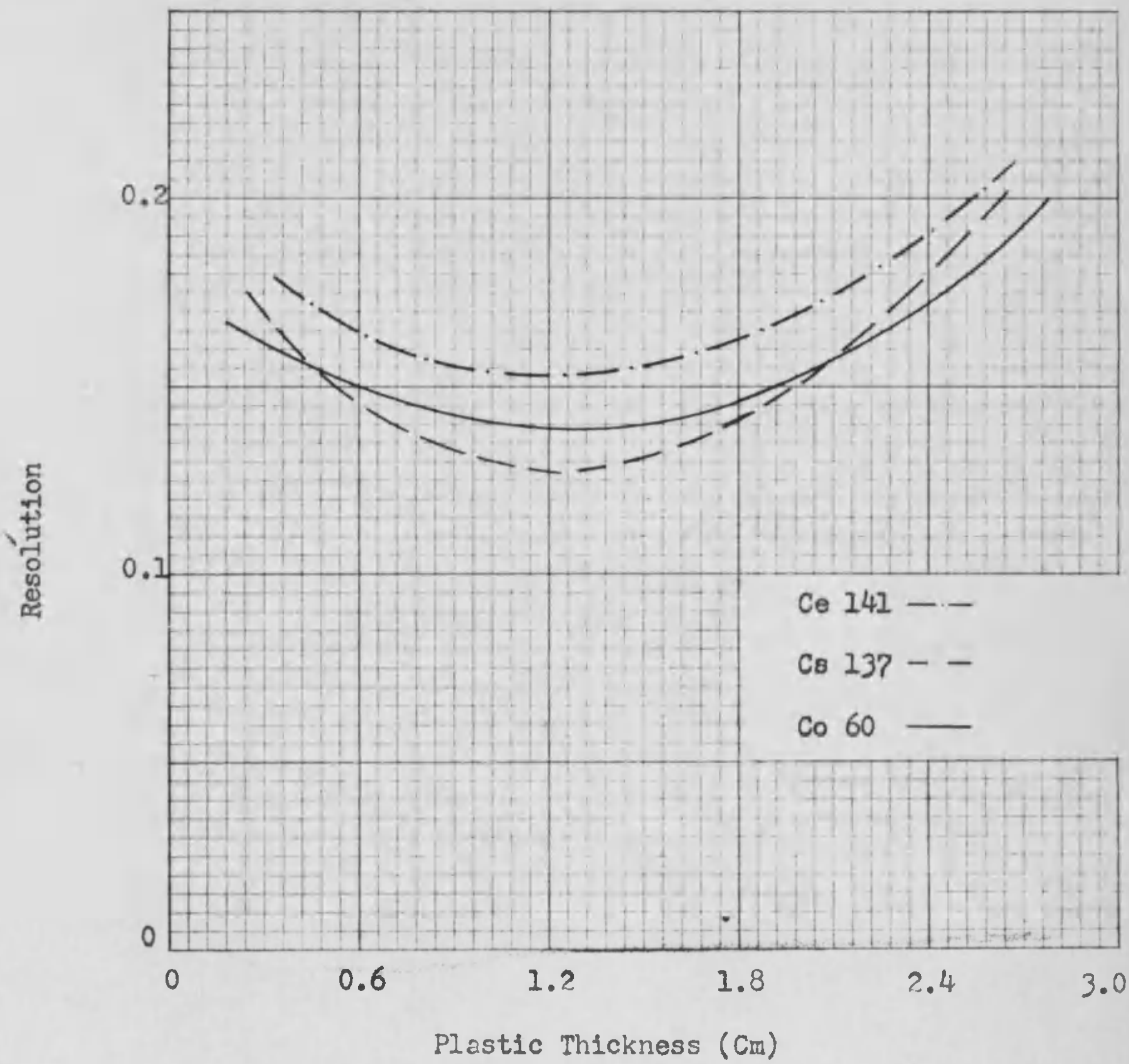


Figure 3.5 -Resolution of the Laminated Detector as a Function of Plastic Thickness for Three Gamma Ray Sources.

This comparison is shown in Figure 3.6 and clearly indicates that in a 1.270 cm plastic which has a maximum photopeak count of about 2800, the maximum count is reduced to about 900 counts by the addition of the opaque shield. The detector with the shield closely approximates a 0.635 cm plastic but the spectrum for the modified detector is slightly less than that for the 0.635 cm plastic. Since most of the interactions in a thicker plastic take place further from the photomultiplier tube, the intensity of the scintillations is degraded somewhat by the plastic. They are observed by the photomultiplier tube at this degraded intensity and the variation of energies near the photopeak is wider, and the resolution consequently is poorer.

A factor that exerted considerable influence on the total count was the optical coupling of the plastic to the photomultiplier tube. It was found that poor coupling could make a 50% difference in the count obtained from the same lead-plastic combination.

It is apparent that the 1.270 cm plastic with a 0.0304 cm lead foil is the optimum thickness to be used over the energy range specified. In the following chapters a Monte Carlo program to calculate the efficiency of the optimum detector will be developed and the efficiency for several gamma sources will be calculated.

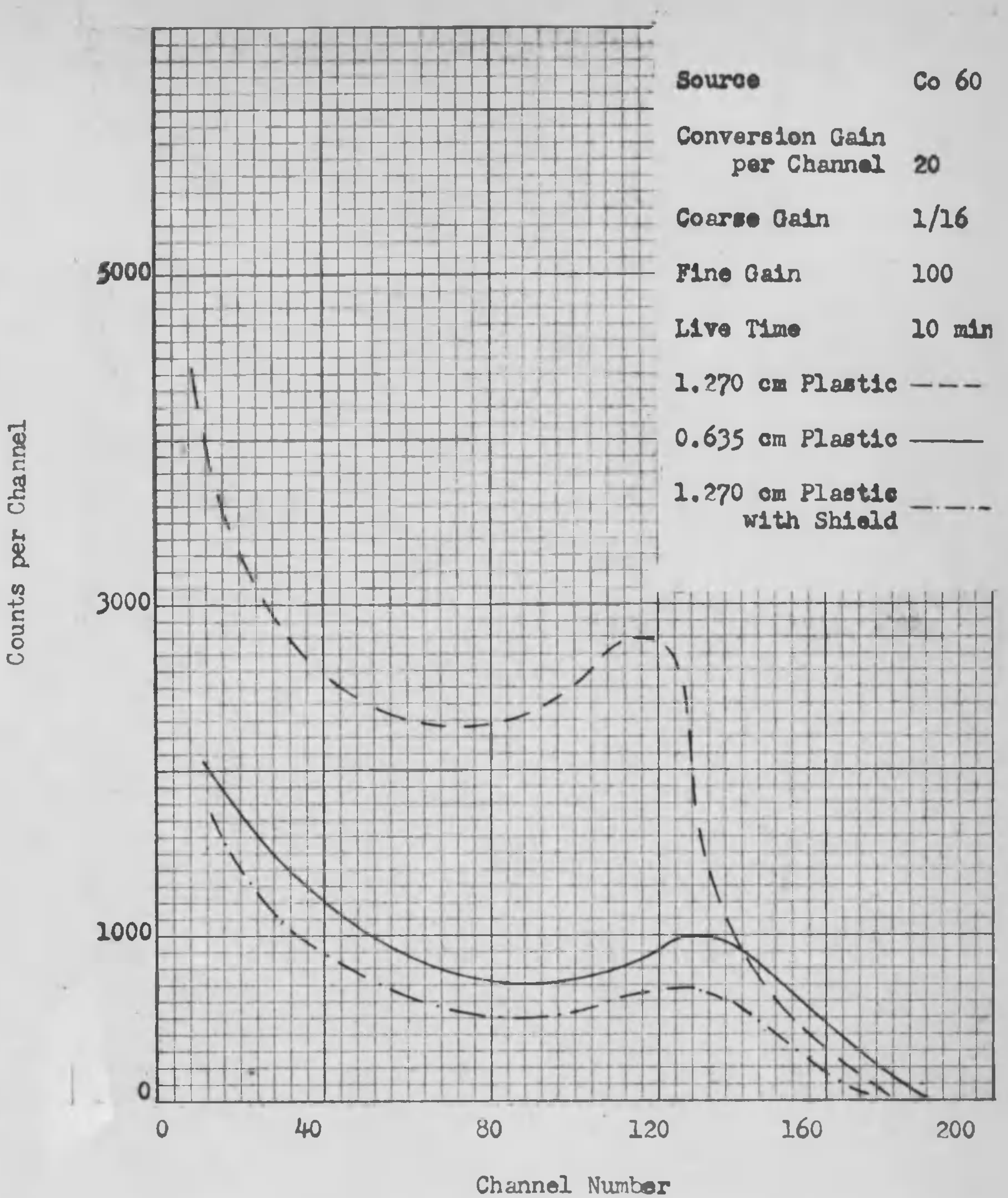


Figure 3.6 -A Comparison of the Spectrum from a 1.270 cm Thick Plastic with an Opaque Shield 0.635 cm from the Front Face, and the Spectrum from 1.270 cm and 0.635 cm Thick Plastic Detectors.

CHAPTER 4

SCINTILLATOR SYSTEM EFFICIENCY

4.1 Intrinsic Efficiency

The next step in discussing the laminated lead-plastic scintillator should be the determination of the efficiency of the detector. The intrinsic efficiency of a scintillation detector can be calculated by the following formula (5):

$$\epsilon = \frac{\int_{\Omega_0}\left[1-\exp\left(-\mu x\right)\right] d\Omega_0}{\Omega_0} \qquad (4.1)$$

where μ is the total absorption coefficient for the material making up the scintillation crystal, Ω_0 is the solid angle subtended by the crystal as measured from the source, and x is the maximum thickness of the crystal.

The above equation will give an estimation of the efficiency of the detector, but will, in most cases give a value higher than the actual one. This is due to the fact that the electronic circuitry rejects some of the smaller pulses. In many complicated system geometries, it is difficult to determine the solid angle. Also in using the above equation, it is assumed that each interaction results in a count and the distance traveled by this photon is the maximum possible in the detector material. Thus the angle at which the photon intersects the detector is ignored, as is the fact that it would be entirely possible for the photon to escape from the detector in a much shorter range than the distance x. A much more accurate method of calculating the efficiency of the detector is the Monte Carlo method.

4.2 The Monte Carlo Method

The Monte Carlo or Random Walk Technique is essentially a statistic compilation from a limited number of individual events, through which it is possible to predict the average behavior of a system of events. The compilation of such a set of data can be done on a desk calculator, or by slide rule, but this can involve much tedious work. Consequently it is much more convenient to use a high speed computer. The modern high speed digital computer can rapidly make the many calculations required in very complex problems, then make intelligent decisions and follow divergent paths based on these decisions. The computer makes these decisions by simply comparing two numbers and then following one path for the larger number, or a second path for the smaller number.

When a gamma ray passes through matter, there may be no interaction between the gamma and the matter, or there might be one of three types of interactions. These three are the compton effect, pair production and the photoelectric effect. All other types of interactions which occur at either very high or very low energies are ignored in this study. One or another of the four events listed above must occur 100% of the time, but each does not occur one-fourth of the time. The linear attenuation coefficients for the various processes are measures of the probability of the occurrence of the particular type of interaction. For example if the photoelectric effect is considered, the probability of a given photon traveling a distance x without having a photoelectric interaction is given by

$$p = \exp(-\tau x) \qquad (4.2)$$

where p is the probability of no interaction and τ is the linear attenuation coefficient for the photoelectric effect. Similarly the probability of no interaction for the compton effect, pair production, or of no interaction of any type can be calculated. The sum of the probabilities of the four events must always equal unity.

If a number lying between zero and unity can be chosen by some random process, it can be compared to the probability of occurrence of each of the four processes, and one of them can be selected as having occurred. For example, assume that the probability for a compton interaction has been determined by Equation (4.2) as 0.625, and the number selected has a value of 0.510. It would then be said that a compton interaction had occurred. However if the random number had been 0.810, it would be concluded that a compton interaction had not occurred, and further checking would be required to determine what type did occur.

In the computer program, the random number is selected by a process which will be discussed in the next section, and compared to the probability for a given type of interaction. If the computer decides that an interaction of the type in question did occur, it proceeds to make certain calculations. If the interaction did not occur, the computer follows a secondary path and makes other calculations. It is this ability of the computer to make such comparisons rapidly and then make logical decisions that makes the Monte Carlo technique possible.

It is also possible to obtain much more information than just the efficiency from the solution to a Monte Carlo program. For example, by proper programing, it is possible to obtain the number of photons of a given energy that have interactions, the number of secondary photons that have interactions, and the number of photons that escape the detector without having any interactions.

4.3 Random Number Generation

In this program, use is made of the computer to generate the random numbers needed in the computations. Obviously the use of the computer to generate random numbers must be based on some system and hence their randomness is open to question. But the random numbers used to determine certain events do not always occur in the same sequence since all parts of the program are not used for each history. There is also the advantage in using a system to generate the numbers, in that numbers will always be generated in the same sequence and the results of a computation can be checked if necessary.

The system used in this program consists of multiplying an eight-digit random number by the factor twenty-three. The number twenty-three was selected since it is a relatively large prime number. The number obtained by the multiplication is then reduced to an eight-digit number by retaining only the eight low order positions. This eight-digit number is then multiplied by twenty-three to obtain the next random number. This system operates on call when needed by the program, and the process can continue indefinitely as the program runs. Provisions are made to stop the program if a random number consisting of all zeros is generated.

The starting random number is included as a part of the input data when a new series of histories is begun. The starting number can have any value. In this thesis a starting number was selected and the same number is used as the starting number for all calculations. This was done to eliminate one variable from the computations and make the comparison of the calculated efficiencies more meaningful.

The value of the random number is limited to numbers greater than zero but less than unity for all computations.

4.4 Computing Equipment

The computer used in solving for the efficiency is the IBM 650 digital computer. It has a two thousand-word drum storage capacity and a sixty-word core storage which provides an immediate access feature. Also there are three four-digit Indexing Registers, and provisions for the employment of floating decimal-point arithmetic. An accounting machine can optionally be employed to give an immediate printed record of the output of the computer as it performs its computations. The program allows the operator to select either to have the answers punched on cards or printed by the accounting machine. This is done by placing a plus sign in the storage entry switches on the computer console for a punched output, or a minus sign for a printed output.

The program to compute the efficiency of the detector was initially programed in a symbolic language, then optimized and placed in machine language by the use of a SOAP X routine developed by the Numerical Analysis Laboratory at the University of Arizona (6). This routine converts the symbols to ten-digit "words" and places these words in storage locations on the computer drum that will enable it to run as fast as possible by minimizing the time the computer "hunts" for the data it needs.

At this point a word about the floating point feature seems in order. This provides a means of automatically keeping track of the decimal point in the long and involved calculations required in the problem. In floating point each word is treated as an eight-digit word with a two digit characteristic in the right two locations. The digits "50" are used as a base, so the value of the characteristics can range from 00 to 99. A characteristic of 50 indicates that the decimal point is to the left of the first position of the eight-digit word, while a characteristic of 49 would show one zero between the first digit and the decimal point. A few examples of floating point are shown in Table II and should make the procedure clear.

Table II: Examples of Floating Point Numbers

Number	Floating Point
0.1234567890	1234567850
123.45678900	1234567853
0.0001234567	1234567047

The reason for discussing the floating decimal point feature is that the program uses floating point in all its computations. However, in some cases it is necessary to first place a number in its normal form in the program, then convert it to floating point at some later time. For example, the number of histories to be considered is first entered in its normal form and one is subtracted from it each time a history is terminated. However, when we compute the efficiency of the system we want the number of histories in floating point. So it is converted to floating point by the computer at this time, and proper account of the decimal point is thus maintained.

The next chapter will describe in detail the steps that the computer goes through to solve the problem.

CHAPTER 5

THE COMPUTER PROGRAM

5.1 General

A general flow diagram of the computer program developed to determine the efficiency of the laminated lead-plastic gamma scintillation detector is shown in Figure 5.1. The procedure for putting the required input into the computer and the data required will be discussed in the next chapter. In this chapter, the equations and general procedure used will be discussed in some detail. The procedures will generally follow the methods for random walk problems developed by Cashwell and Everett (7).

The Monte Carlo program, as it will be used here, consists of following a certain number of individual monoenergetic gamma rays as they pass through matter. Determination is made as to whether the ray passes through the material without experiencing an interaction, or if it does have an interaction, what kind it was. As was discussed in section 2.1, each interaction produces at least one electron which has some energy equal to or less than the energy of the initial gamma. It is assumed that any of these electrons which reach the plastic portion of the scintillator will lose this energy by absorption and will result in a count.

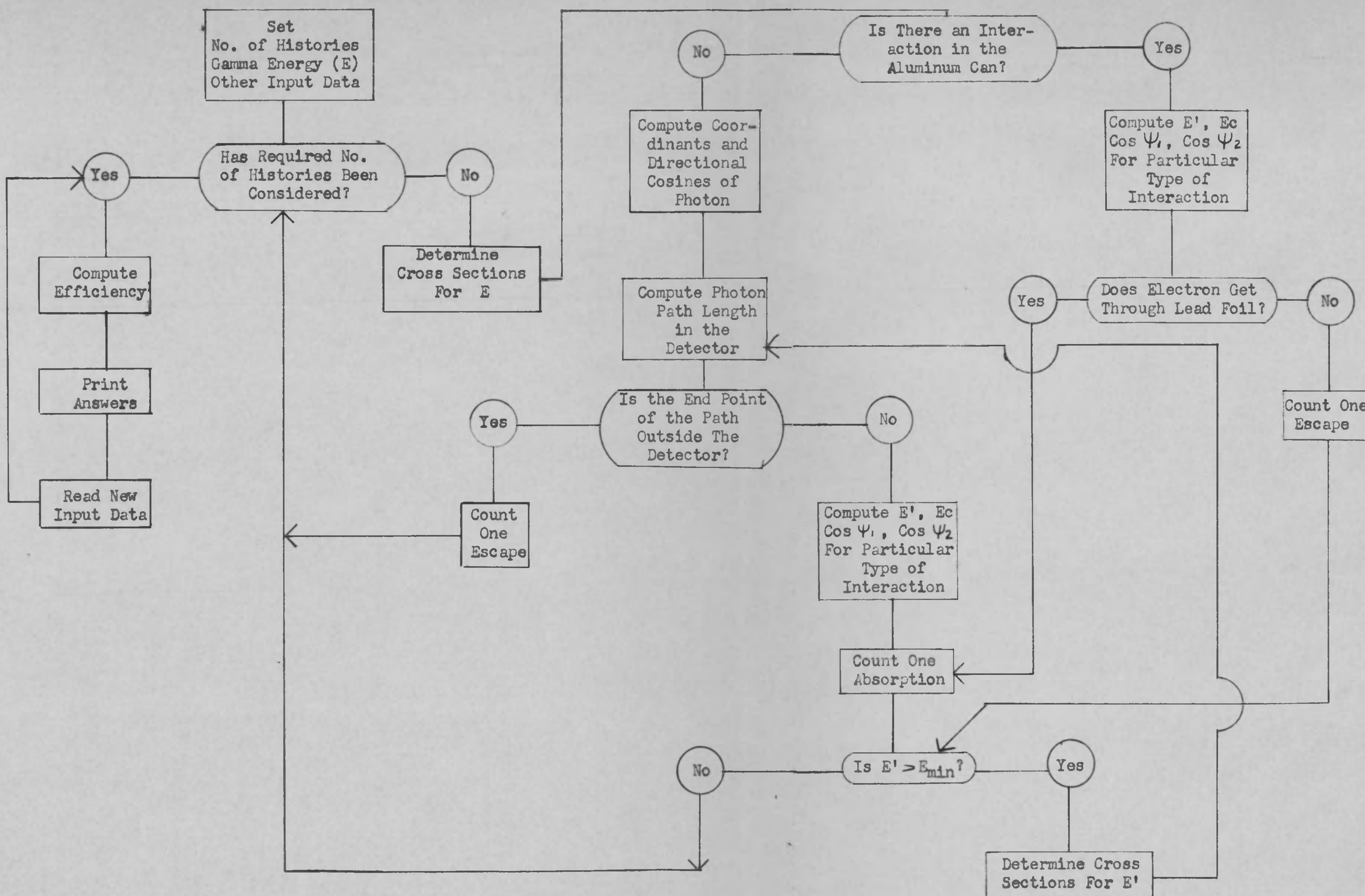


Figure 5.1 -General Flow Diagram For the Computer Program to Calculate the Detector Efficiency.

This is reasonable since an electron can be totally absorbed in a cubic centimeter of a phospher (2). Each history is followed until the photon either escapes or is absorbed by some process within the detector. If a secondary photon is produced by the interaction, it is treated as a new photon and is traced in the same manner as the primary photon was. The efficiency of the detector is computed by dividing the number of primary photons that were absorbed by the total number of photons considered.

To relate the above process to the specific detector used in this experiment, the materials that make up the detector and the geometry of the detector system are used as parameters upon which the computer will make many of its decisions. As an integral part of the program, the linear attenuation coefficients for the three types of interactions are stored in the drum storage of the computer. The values of these coefficients are shown in Appendix B, and are used within the program to solve for the photon path length, type of interaction, and other data.

5.2 Assumptions

In drawing up the computer program the following assumptions were made:

a. The source is a monoenergetic point source located on the axis of the detector system.

b. Any electron that reaches the laminated detector will be totally absorbed and an absorption will be counted.

c. If a photoelectric effect occurs, all the energy of the incident photon is transferred to the electron produced.

d. If a pair production interaction occurs, the positron is annihilated at the point of interaction and the two secondary photons are considered to have been born at this point.

e. The direction of the electron produced in the photoelectric and pair production interactions will have the same direction as that of the incident photon.

f. When a secondary photon reaches an energy of 0.05 mev, it will be forgotten. This is E_{min} in the program.

5.3 Location of the Interaction

The initial steps in the program provide the means of storing the input information in the proper locations in the computer. Among the data to be stored is the number of histories to be considered. This information is placed in one of the indexing registers; and by subtracting one from this register each time a history is terminated, an account of the number of histories can be maintained. Each time a history is terminated the index register is checked to see if it is zero. At this point, the computer makes the first of its many decisions.

If the indexing register is zero, it means that the required number of histories has been followed. This is shown in Figure 5.1. Now the efficiency of the detector is determined by subtracting the number of absorptions caused by secondary photons from the total number of absorptions and dividing by the total number of histories. Since the efficiency is defined as the ratio of the number of photons that are absorbed to the total number of photons that strike the detector (8), the result of the above calculations will be the efficiency of the laminated detector for the particular photon energy traced. The output information will be punched or printed in a format that will be described in the next chapter. All the storage locations are reset to zero, another input data card is read by the computer, and a new set of histories is begun.

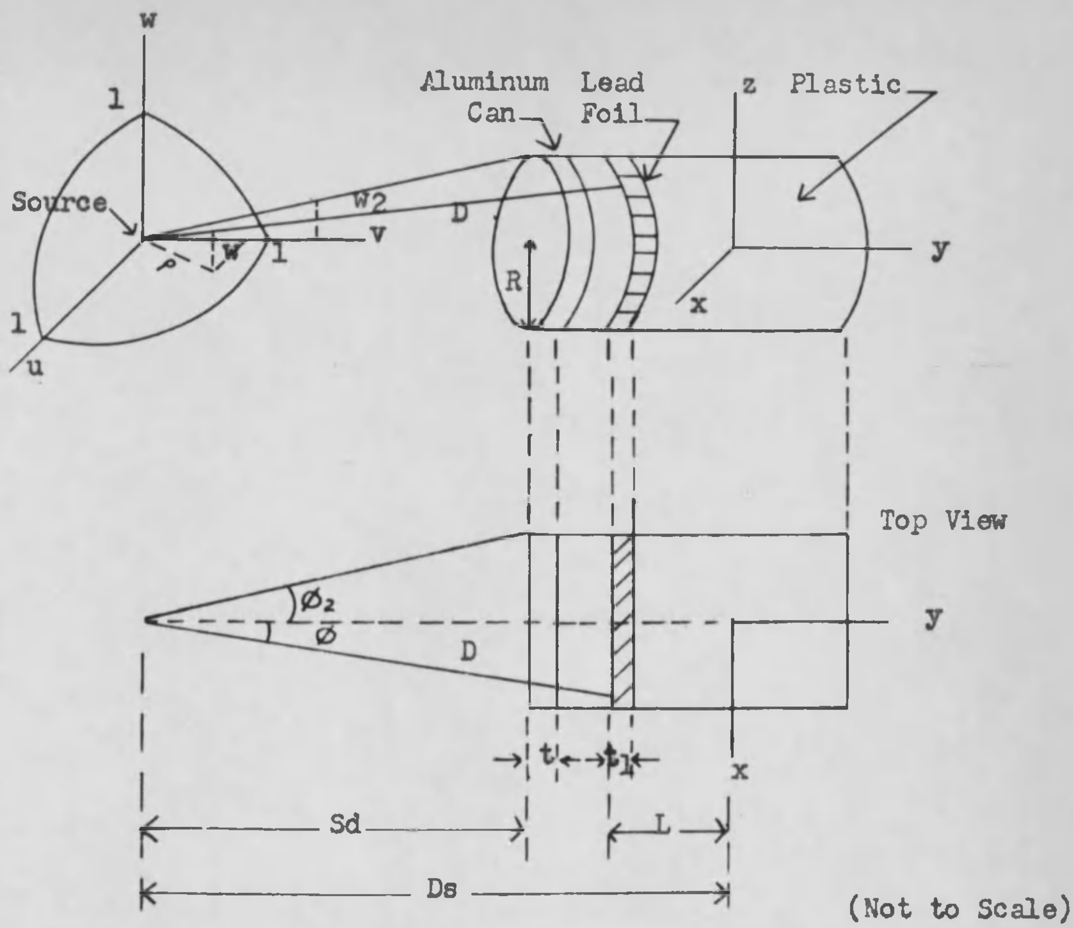
If, on the other hand, the indexing register was not zero the required number of histories has not been traced and the computer takes the second path in the program. The first step in this portion is to determine the linear attenuation coefficients for the energy of the incoming photon. This is performed by the computer through the use of a table look-up procedure whereby the proper values of the coefficients are extracted from the table in the computer storage and placed in known locations where they will be available to the program when needed. At this point it is necessary to determine if the photon has any type of interaction as it passes through the aluminum can on its way to the laminated detector. This can be determined by

$$r_1\text{-}\exp(\mu_o\ t) \qquad (5.1)$$

where μ_o is the total attenuation coefficient for aluminum, r_1 is a random number, and t is the thickness of the can. Since the exponential gives a probability of not having an interaction, it can be said that if the above expression is negative there is no interaction in the can, and the photon passes through the cover to interact with the lead-plastic detector. If the expression is positive the photon did experience an interaction in the can and the method of handling these computations will be discussed in Section 5.7. Throughout this paper, r_n refers to a random number, where n denotes the sequential order of the random numbers.

5.4 Interaction in the Laminated Detector

Once it has been determined that the photon has passed through the aluminum can, the next step is to compute the coordinates and the directional cosines of the gamma ray as it enters the lead-plastic portion of the detector. As shown in Figure 5.2, the center of the coordinate system is at the center of the lead-plastic portion. The directional cosines are found by choosing a point uniformly distributed on a unit sphere centered on the point source. From



u, v, w	-Direction Cosines	D	-Distance Photon Travels From Source to Detector
w_2	-Maximum value of Direction Cosine in z Direction	t_1	-Thickness of Lead Foil
$\emptyset_2$	Maximum Angle Between Line of Flight of the Photon and y Axis	t	-Thickness of Aluminum Can
		Sd	-Distance From Source to Face of Aluminum Can

Figure 5.2 -A Diagram Showing the Relationships Between the Various Parameters of the Optimum Laminated Detector Used in the Computer Program Calculations.

Figure 5.2 it can be seen that the maximum value that the directional cosine in the z direction (w_2) can have is given by

$$w_2 = \frac{R}{\left[R^2 + (Ds-L)^2\right]^{\frac{1}{2}}} \qquad (5.2)$$

It can also be seen that the maximum value of the angle ϕ_2 in the xy plane can be given by

$$\phi_2 = \arc\tan \frac{R}{Ds-L} \qquad (5.3)$$

It can be shown that the values of ϕ and w can be randomly determined through the use of Probability Density Functions (7) as

$$w = w_2(2r_2-1) \qquad (5.4)$$

$$\phi = \phi_2(2r_3-1) \qquad (5.5)$$

Referring to Figure 5.2, it is apparent that the remaining two direction cosines can be calculated by first finding ρ from

$$\rho = \left[1-w^2\right]^{\frac{1}{2}} \qquad (5.6)$$

Then

$$u = \rho \sin \phi \qquad (5.7)$$

$$v = \rho \cos \phi \qquad (5.8)$$

The distance from the source to the face of the detector can be found by

$$D = \frac{Ds-L}{\cos \phi} \tag{5.9}$$

Now the coordinates of the point of intersection of the gamma ray with the lead plastic detector are

$$x = D \sin \phi \tag{5.10}$$

$$y = D \cos \phi \tag{5.11}$$

$$z = D \frac{W}{\rho} \tag{5.12}$$

The next problem is to determine the path length of the photon in the detector. The distance that a photon travels in a material can be determined randomly by assuming a probability of no interaction of r_4 and finding a path length that would give this probability. To do this, Equation (5.1) can be written as

$$r_4 = \exp(-\mu_{ot}\ell) \tag{5.13}$$

where ℓ is the path length to be determined and μ_{ot} is a total attenuation coefficient for lead and plastic. μ_{ot} can be determined by the following formula (3)

$$\mu_{ot} = (\mu_{ol})(W_l) + (\mu_{op})(W_p) \tag{5.14}$$

where μ_{op} and μ_{ol} are the total attenuation coefficients for plastic and lead respectively and W_p and W_l are the fractions by weight of plastic and lead in the laminated detector. The weights of the various thicknesses of plastics and lead foils used in the experiments can be found in Appendix A. By taking the natural logarithm of both sides, Equation (5.13) can be written as

$$\ln r_4 = -\mu_{ot}\ell \tag{5.15}$$

or rearranging

$$\ell = \frac{1}{\mu_{ot}} \ln\left(\frac{1}{r_4}\right) \tag{5.16}$$

The direction cosines of the photon do not change as it moves along this path length. It is now possible to determine the coordinates of the end points of the path length as follows:

$$x' = x + u\ell \tag{5.17}$$

$$y' = y + v\ell \tag{5.18}$$

$$z' = z + w\ell \tag{5.19}$$

Each coordinate of the end point of the path length is now checked to see if the end point is in or out of the detector. This is done by checking each coordinate against the proper dimension of the laminated detector as follows:

$$|x'| - R = k_1 \tag{5.20}$$

$$|y'| - L = k_2 \tag{5.21}$$

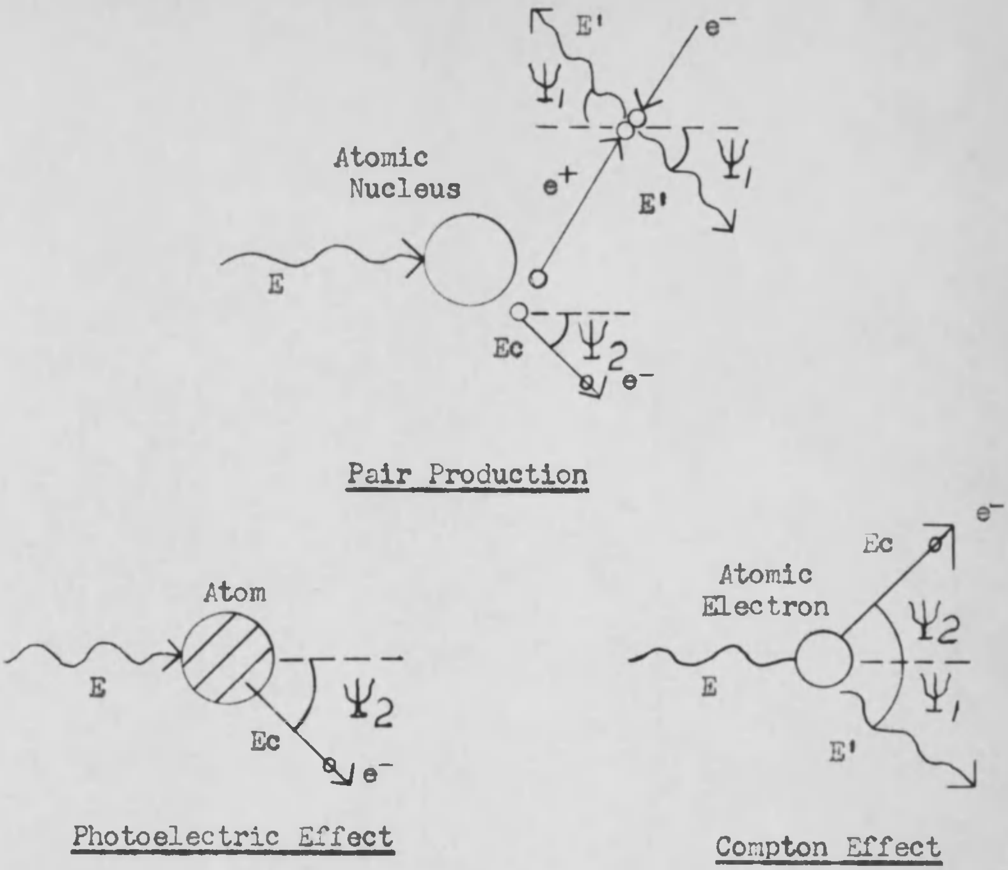
$$|z'| - R = k_3 \tag{5.22}$$

If one of the above equations is positive, the photon has passed through the detector without having an interaction of any type. So one escape is recorded and the computer returns to the starting point and begins a new history. If all the above equations are negative, the photon has experienced an interaction in the detector and the type must now be determined.

5.5 Type of Interaction

The first step in this portion of the program is to convert the energy of the incoming photon to a rest mass energy by dividing the energy in mev by the electron rest mass. All the computations are carried out in these units. As mentioned previously, there are three types of interactions possible in the scintillator. The probability of any of these occurring is given by the linear attenuation coefficient for that particular type of interaction. The fraction of the time that a photoelectric effect would occur is given by dividing the photoelectric cross section (τ) by the total cross section (μ_0). We then select a random number r_5 and if this number is less than the fraction $\frac{\tau}{\mu_0}$, a photoelectric interaction has occurred. The mechanics of this effect are shown in Figure 5.3 and the equations to be solved by the computer program are as follows

$$Ec = E \tag{5.23}$$



E -Energy of Incoming Photon in Rest Mass Units

E' -Energy of Secondary Photon in Rest Mass Units

Ec -Energy of Electron in mev

Figure 5.3 -A Diagram Showing the Relationship Between the Incoming Photon, Secondary Photon, Scattered Electron, and Scattering Angles in the Three Gamma-ray Interaction Processes.

$$\cos \Psi_2 = 1 \tag{5.24}$$

Provisions are also made to set the energy of the secondary photon and its scattering angle to zero.

But if the random number r_5 is greater than the ratio $\frac{\tau}{\mu_o}$, the ratio for pair production $\frac{K}{\mu_o}$ must be added to the previous ratio and this sum is checked against the random number (r_5). If this number is greater than the ratio $\left(\frac{\tau}{\mu_o} + \frac{K}{\mu_o} \right)$, pair production has occurred. This effect is also shown in Figure 5.3 and the equations to be solved are

$$Ec = 1/2\ (E-2m_oc^2) \tag{5.25}$$

$$E' = m_oc^2 \tag{5.26}$$

$$\cos \Psi_1 = 1 \tag{5.27}$$

$$\cos \Psi_2 = \pm\ \pi r_6 \tag{5.28}$$

If it is determined that a pair production interaction did not occur, then the interaction must have been a compton effect. This is the most likely effect in the detector. In fact, it is the only possible effect that will occur in the plastic portion of the detector. This type of interaction is illustrated in Figure 5.3. It can be shown that the following equations will provide the necessary data (7)

$$E' = \frac{E}{1 + sr_7 + 2(E-s)r_7^3} \tag{5.29}$$

$$s = \frac{E}{1 + 0.5625E} \qquad (5.30)$$

$$Ec = (E-E') \qquad (5.31)$$

$$\text{Cos}\,\Psi_1 = 1 + \frac{1}{E} - \frac{1}{E'} \qquad (5.32)$$

$$\text{Cos}\,\Psi_2 = \frac{E-E'\text{Cos}\,\Psi_1}{(E-E')^2 + 2(E-E')^{\frac{1}{2}}} \qquad (5.33)$$

All the values needed to record the absorption of the electron and to follow the secondary photon to its termination have now been calculated.

5.6 Termination of the History

Using the values for the data calculated in the previous section the next step is to record one absorption in the total absorption counter, and also to record one absorption in the storage location equal to the energy of the electron. If there was no secondary photon produced, this terminates the history and the computer returns to the start of the program to begin a new history.

But if a secondary photon was produced by the interaction in the detector, this photon's energy must be checked to see if it is greater than E_{min}, the cut-off energy. If it is less than E_{min}, the history is terminated and the computer returns to start a new history. If it is greater, it is treated as a new photon of Energy E' and its history is traced. It can be shown (7) that the new directional cosines are:

$$u' = \left[\sin\Psi_1 \cos(\pi r_8)wu - \sin(\pi r_8)v\right] / \rho + (\cos\Psi_1)u \quad (5.34_a)$$

$$w' = w' \cos\Psi_1 - \sin\Psi_1 \cos(\pi r_8) \quad (5.34_b)$$

$$v' = \left[\sin\Psi_1 \cos(\pi r_8)wv - \sin(\pi r_8)u\right] / \rho + (\cos\Psi_1)v \quad (5.34_c)$$

The values for the interaction attenuation coefficients are then determined for the energy of the secondary photon using the table look-up procedure previously described. A count of one is added to the running total of secondary photons and the computer returns to a determination of a path length for this secondary photon. This is shown graphically in Figure 5.1.

5.7 Interaction in the Aluminum Can

If there had been an interaction between the photon and the aluminum can, the computer would have followed a slightly different path. The procedure to determine the type of interaction and the values of the equations described in Section 5.5 is the same except that the attenuation coefficients for aluminum are used, instead of those for lead and plastic. The electron produced is, of course, produced in the aluminum can and still must travel through the lead foil before it reaches the plastic where it loses its energy and produces a scintillation. The range of electrons is very short and they can be totally absorbed in small thicknesses of most materials. The range of the electron in lead can be calculated by writing Equation (3.1) as

$$Rn = 0.03625\ Ec^{n} \qquad n = 1.265-0.0954\ \ln Ec \qquad (5.35)$$

The effective thickness of the lead to the passage of the
The effective thickness of the lead to the passage of the
electron is given by

$$t_{eff} = \frac{t}{\cos \phi_2} \qquad (5.36)$$

The range of the electron can then be subtracted from the effective thickness of the lead foil and if the range is greater the electron has passed through the foil and is absorbed in the plastic. The computer then goes to the termination of the history section of the program. If the electron is absorbed in the foil, an escape is recorded and the computer proceeds to the check of the secondary photon. These paths are shown on Figure 5.1.

This completes the discussion of the General Flow Diagram for the computer program. Mention should be made of the fact that there are several sub-routines used within the program to perform various calculations such as random number computation, and calculation of the sine of an angle. These sub-routines can be used several times within the program and save many steps. The next chapter will discuss the input and output format of the program and will give the results of the efficiency calculation for several energies.

CHAPTER 6

PROGRAM INPUT, OUTPUT AND RESULTS

6.1 Input Format

In this chapter, the input and output formats are discussed to enable the reader to operate the program. The results of a series of computations using this program also will be presented.

Prior to attempting to place input data in the program, it is necessary to understand the program so the data will be entered in the proper form. All the input information for both the program and the input data is entered on a standard eight-word card. The program itself is entered in a five-instruction per card format produced by the computer during the optimization and translation phase. These program cards are preceeded by a two-card loading routine and are then loaded into the computer first. The input data cards follow and may number as many as desired.

Since the input data is also placed on eight-word cards the number of pieces of input information is limited to eight. Naturally, the elements that vary from problem to problem should be entered as input. Since these number more than a single card can hold, eight pieces of data were selected to be entered and the other variables can be calculated from these eight. The elements selected were the number of histories to be followed, the energy of the incoming photon, the starting random number, the thickness of lead foils, the distance L, the maximum angle ϕ_2, the fraction by weight of plastic, and the distance Sd. These must always be entered in the same order and in the same format. The first two elements are entered in normal form, but the last six are entered in floating point. An example of a properly prepared input card is shown in Figure 6.1. It should be mentioned that the gamma energy is determined by writing an energy of 1.33 mev as 133. Then an energy of 0.67 mev would be written as 067, and one of 0.067 as 0067.

Thus this program can be used to solve problems for any thickness of plastic or lead foils, and for any source distance Sd from the can face. It can also solve problems for any gamma energy between 0.05 and 3.0 mev. These limits are caused by the attenuation coefficients placed in the storage. The range could be extended by placing more coefficients in the drum storage of the computer. The program is also limited to a monoenergetic source; but for a multienergetic source, each energy could be calculated separately, then combined by hand at the end of the problem.

An important point to understand is that a plus sign must be entered in the tenth digit position of each word of the input data card. If this is not done, the input unit of

Word 1 ▯	Word 2 ▯	Word 3 ▯	Word 4 ▯	Word 5 ▯	Word 6 ▯	Word 7 ▯	Word 8 ▯
0000001000	1170000000	1532738650	3040000049	6350000050	3770000050	7760000050	6350000050

Word 1 -No. of Histories	1000
Word 2 -Gamma-ray Energy	1.17 mev
Word 3 -Starting Random Number	0.15327386
Word 4 -Thickness of Lead	0.0304 cm
Word 5 -Distance L	0.635 cm
Word 6 -Maximum Angle (ϕ_2)	0.377 rad
Word 7 -Percent by Weight of Plastic	77.6%
Word 8 -Distance Sd	0.635 cm

▯ -Indicates a Plus Punch

Figure 6.1 -Example of the Input Data Card for the Monte Carlo Computer Program.

the computer will reject the card. Another very important point is that, while many programs require the input card to be "load punched" in digit position one of the first word, this must not be done to these cards. If it is done the computer will accept the information as part of the program deck and not as input information.

To start the program, the numbers 70 1951 0034 are placed in the storage entry switches of the computer console by hand. The two-card loading routine, the program deck, and the data cards are placed in the input unit of the computer and run is started. A copy of the program deck in five-instruction per card format can be found in the Library of the Numerical Analysis Laboratory at the University of Arizona.

6.2 Output Format

As previously mentioned, the operator selects the type of output desired by placing a plus or minus sign in the storage entry switches when he starts the program. If the punched output is selected, it can be printed later by the accounting machine.

The output will consist of three cards or three lines printed on a sheet for each data card entered. The first twenty-one elements of information will have the total number of absorptions by electron energy recorded. The first three digits in each element identify the energy in the manner described above, while the last four digits specify the total number of absorptions of that energy. Word twenty-two has the total number of absorptions of all energies in the four low order digit positions. Word twenty-three has the total number of photons that escaped the detector without having any type of interaction in the same format as word twenty-two. The efficiency of the detector for the given gamma energy is shown in word twenty-four in floating point form. An example of the third card of the three-card output is shown in Figure 6.2.

6.3 Results

The program was run to determine the efficiency of the detector in counting the sources used to determine the optimum thickness of plastic to be used for gamma counting. All of the sources except the Cobalt 60 sources emit a single gamma and for these, one thousand histories were traced. For the Cobalt 60 which emits two gammas, five hundred histories were followed for each and the results were added together. The results of these computations are tabulated in Appendix C.

As shown in Appendix C, the efficiency of the optimum detector for the three gamma energies under consideration varies from 17.8% to 86.6%. The latter figure is for the Ce 141 source. The reason for such a high efficiency is that at the gamma ray energy of 0.145 mev, the linear

Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
1000000001	1500000000	2000000000	2500000000	3000000000	0000000018	0000000088	1200000050

Word 1 indicates one absorption of a 1.0 mev electron.
Word 2 through 5 indicates no absorptions at those energies.
Word 6 indicates there were a total of 18 photons absorbed.
Word 7 indicates there were 88 escapes of primary photons.
Word 8 indicates an Efficiency of 12%.

Figure 6.2 -An Example of Card Three of the Three-card Output From the Computer Program.

photoelectric coefficient is a maximum; and is about two orders of magnitude greater at the maximum then at any other point. Since the path length of the photon varies as 1/K where K is the photoelectric coefficient, a large value of K will result in a short path length in the material. A short path length will increase the probability of an interaction and give a high efficiency for the detector. This computed value is probably higher than the actual value, and if many more histories were tabulated, a more realistic efficiency would be obtained. The results of the program calculations show that the efficiency of the detector increases as the incident gamma energy is decreased. This is as expected; since, as the energy decreases the probability of interaction increases, and more absorptions take place.

The program was also run for a 2.540 cm and 0.635 cm plastic using the Co 60 source. It was determined that the 2.540 cm plastic had an efficiency of 20.2%, and the 0.635 cm plastic had an efficiency of 14.8%. This indicates that the efficiency will increase as the plastic thickness is increased. This result agrees with the experimental results shown in Figure 3.2, 3.3, and 3.4.

The efficiency of a scintillation detector is on the order of 100 times greater than that of a Geiger-Muller counter. The efficiency of a Geiger-Muller counter for most cathode materials is between 0.02% and 0.26% (8). The values of the efficiency calculated by the Monte Carlo program are within 100 times of these values except for the Ce 141 source.

The major drawback to this method of calculating efficiencies is the excessively long running time of the program. To compute 100 histories requires the computer approximately twelve minutes. There appears to be no satisfactory way to scale the program to shorten the running time and not affect the statistical accuracy of the results.

6.4 Energy Absorption Ratio

Another value that can be determined from the results of the computer computations is the Energy Absorption Ratio. This ratio can be defined as the total amount of energy absorbed in the plastic detector from the gamma rays incident on it divided by the total incident energy. The absorbed energy can be determined by multiplying the total number of absorptions in any energy interval by the average value of the energy interval, then summing all these values for all the energy intervals. When these calculations are carried out for the computer results shown in Appendix C, it is found that the energy absorption ratio for Ce 141 is 0.259; for Cs 137 it is 0.108; and for Co 60 it is 0.078. This ratio is a measure of the ability of the material, in this case the plastic detector, to absorb radiation incident on it. This ratio was calculated by hand in this problem, but with a few modifications, the computer could be made to perform this calculation and punch or print the answers directly.

CHAPTER 7

CONCLUSIONS

7.1 The Laminated Detector

The 1.270 cm plastic detector laminated with 0.0304 cm of lead is the optimum thickness for a plastic scintillator. Thicker plastics will give much higher count rates, and in the thicknesses used here, internal absorption of light pulses by the detector material did not appear to cause any problems. But as the plastic becomes thicker the resolution of the detector becomes worse. When the plastic was too thin, many of the photons passed through with no interactions and the result was a small count in the spectrum, a broad photopeak, and poor resolution. In all the detector systems tested, the resolution was very poor, and in no case was the detector able to resolve the two peaks in the Cobalt 60 spectrum. It appears that any action to increase the count in the photopeak results in a poorer resolution and increased counting in the valley. Hines and Cardarelli found generally the same effects in working with conical plastic scintillator (9).

It was found that if the detector was calibrated with a known source it would be possible to identify other monoenergetic gamma sources. In Figure 7.1 a detector was calibrated with Cobalt 60. It was assumed that the energy

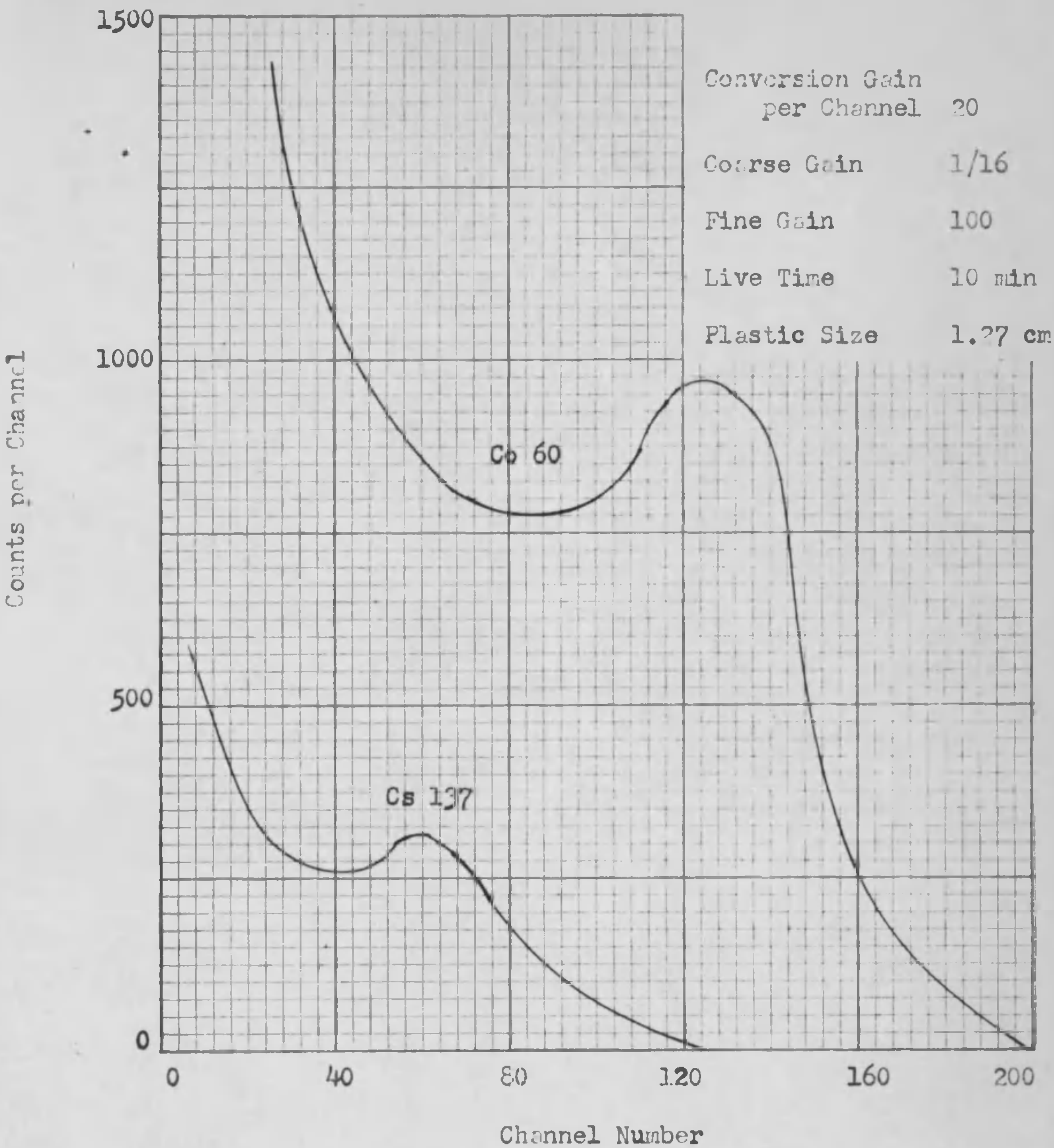


Figure 7.1 -A Comparison of the Cs 137 and Co 60 Spectrum Using the Optimum Laminated Scintillator Detector. The Co 60 Source Was Used to Calibrate the Multi-channel Analyzer.

of the photopeak was 1.25 mev and by a simple proportion, the photopeak of the other source was found at an energy of 0.635 mev which would identify the other source as Cs 137. However, it appears that a laminated lead-plastic scintillation detector of this type has little practical value.

7.2 The Computer Program

The computer solution of a Monte Carlo calculation of the efficiency of the laminated detector yields good results. In addition, much information about the behavior of the photons in the detector can be obtained from such a program. This information is not available from a simple calculation of the intrinsic efficiency of a detector system. This program is limited to the geometry of a system such as that described in Figure 5.1; however it can be modified to accept different geometries and different materials. The main drawback to the program is the long running time.

7.3 Areas for Further Work

Further work on the laminated detector could continue using different elements as foils with the object of increasing the ratio of counts in the photopeak to the compton background in the gamma spectrum. Plastics of other shapes could also be used as detectors.

The computer program offers many opportunities for further work. Attempts should be made to shorten the running time in some manner without losing the accuracy. The program could also be modified to accept other geometries. A most promising use of the program comes from the fact that plastic has a response to gamma radiation very much like the human tissue. As shown in Section 6.4 the energy absorption ratio can be calculated from the results of the computer computations. By modifying the program so that the geometry used in the program can be varied to approximate the organs in the human body, the amount of energy absorbed by the organ could be calculated. A procedure such as this offers a real opportunity to extend our knowledge of the effects of radiation on parts of the human body and to make some accurate estimations as to the amount of energy an organ absorbs from a given radiation source.

APPENDIX A

WEIGHT OF PLASTIC SCINTILLATORS AND LEAD FOILS

Each lead foil is 4.45 cm in diameter, 0.0152 cm thick, and weighs 3.1 grams.

Each plastic scintillator is also 4.45 cm in diameter. The weight of each scintillator by thickness is shown below.

Table III: Weights of Plastic Scintillators

Thickness of Scintillator (cm)	Weight (Grams)
5.08	96.4
2.54	42.0
1.27	21.4
0.64	10.9
0.32	6.3
0.16	2.8

APPENDIX B

LINEAR ATTENUATION COEFFICIENTS

The following linear attenuation coefficients for the three materials making up the detector were determined using the graphs for the mass attenuation coefficients shown in Evans (3). The linear attenuation coefficients were calculated by multiplying the value of the mass attenuation coefficients determined from the graph for the particular energy by the density (ρ) of the material concerned. The results of the computations are shown in Tables IV, V, and VI. These coefficients are used as constants in the Monte Carlo computer program and must be placed in computer memory with the program data.

Pilot Chemicals Inc., produced the scintillation crystals for this experiment. The composition of these Pilot B plastic crystals is given as being 100% hydrocarbon. The ratio of hydrogen to carbon is 1.10, and the ratio by weight is 0.0916. The fraction of hydrogen by weight is 0.0839, the fraction of carbon by weight is 0.916, and the density of the crystal is 1.02 grams per cubic centimeter. Cline (1) has shown that the use of the attenuation coefficients for water are accurate approximations of the coefficients for this type of plastic. The graphs for water were used in determining the values in Table IV.

Table IV: Linear Attenuation Coefficients for Plastic ($\rho = 1.02$ grams/cm^3)

Energy (mev)	Photo-electric (cm^{-1})	Pair Production (Cm^{-1})	Total (Cm^{-1})
0.05	0.015	0.000	0.204
0.06	0.013	0.000	0.199
0.07	0.008	0.000	0.189
0.08	0.005	0.000	0.183
0.09	0.003	0.000	0.179
0.10	0.002	0.000	0.173
0.15	0.000	0.000	0.153
0.20	0.000	0.000	0.150
0.25	0.000	0.000	0.143
0.30	0.000	0.000	0.135
0.40	0.000	0.000	0.104
0.50	0.000	0.000	0.097
0.60	0.000	0.000	0.091
0.70	0.000	0.000	0.084
0.80	0.000	0.000	0.079
0.90	0.000	0.000	0.075
1.00	0.000	0.000	0.071
1.50	0.000	0.000	0.061
2.00	0.000	0.000	0.049
2.50	0.000	0.000	0.043
3.00	0.000	0.000	0.039

Table V: Linear Attenuation Coefficients for Aluminum ($\rho = 2.7$ grams/cm^3)

Energy (mev)	Photo-electric (cm^{-1})	Pair Production (Cm^{-1})	Total (Cm^{-1})
0.05	0.430	0.000	0.837
0.06	0.243	0.000	0.675
0.07	0.135	0.000	0.567
0.08	0.095	0.000	0.486
0.09	0.065	0.000	0.459
0.10	0.024	0.000	0.431
0.15	0.014	0.000	0.378
0.20	0.005	0.000	0.351
0.25	0.000	0.000	0.324
0.30	0.000	0.000	0.270
0.40	0.000	0.000	0.243
0.50	0.000	0.000	0.219
0.60	0.000	0.000	0.210
0.70	0.000	0.000	0.196
0.80	0.000	0.000	0.186
0.90	0.000	0.000	0.175
1.00	0.000	0.000	0.165
1.50	0.000	0.000	0.135
2.00	0.000	0.000	0.116
2.50	0.000	0.003	0.105
3.00	0.000	0.005	0.095

Table VI: Linear Attenuation Coefficients for Lead (ρ = 11.35 grams/cm^3)

Energy (mev)	Photo-electric (cm^{-1})	Pair Production (Cm^{-1})	Total (Cm^{-1})
0.05	55.280	0.000	56.900
0.06	29.000	0.000	30.060
0.07	17.740	0.000	19.300
0.08	12.670	0.000	14.200
0.09	83.570	0.000	85.000
0.10	55.420	0.000	56.750
0.15	16.960	0.000	18.150
0.20	8.500	0.000	9.650
0.25	5.100	0.000	6.240
0.30	2.880	0.000	3.860
0.40	1.590	0.000	2.390
0.50	0.850	0.000	1.590
0.60	0.568	0.000	1.420
0.70	0.349	0.000	1.030
0.80	0.318	0.000	0.910
0.90	0.220	0.000	0.790
1.00	0.204	0.000	0.770
1.50	0.097	0.018	0.580
2.00	0.062	0.051	0.510
2.50	0.047	0.085	0.480
3.00	0.036	0.114	0.460

APPENDIX C

Table VII: Results of Computer Calculations

Energy Interval (mev)	Total Number of Absorptions per Interval		
	Ce 141	Cs 137	Co 60
0.00-0.05	852	83	32
0.05-0.06	39	11	4
0.06-0.07	11	8	4
0.07-0.08	7	13	3
0.08-0.09	6	6	5
0.09-0.10	13	14	3
0.10-0.15	89	30	15
0.15-0.20	0	27	7
0.20-0.25	0	31	12
0.25-0.30	0	17	10
0.30-0.40	0	59	8
0.40-0.50	0	56	6
0.50-0.60	0	0	10
0.60-0.70	0	0	11
0.70-0.80	0	0	10
0.80-0.90	0	0	18
0.90-1.00	0	0	32
1.00-1.50	0	0	12
1.50-2.00	0	0	0
2.00-2.50	0	0	0
2.50-3.00	0	0	0
Total number Absorptions	1017	355	211
Total number Escapes	134	784	822
Efficiency	86.6%	21.6%	17.8%
Energy Absorption Ratio	0.259	0.108	0.078

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