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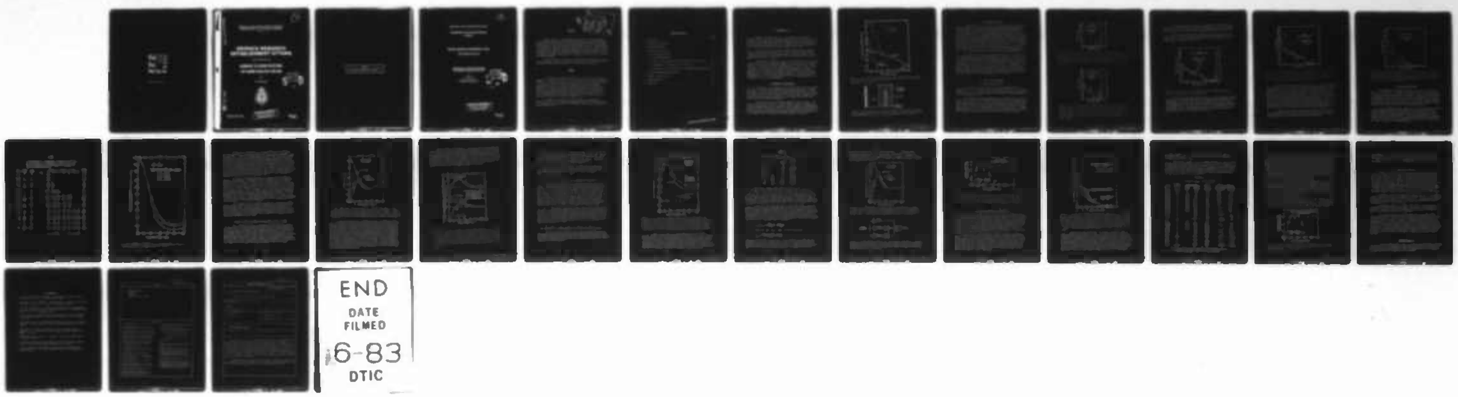

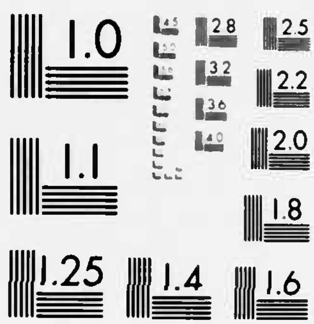

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RESEARCH AND DEVELOPMENT BRANCH
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DREO REPORT NO. 859

CADMIUM TELLURIDE DETECTORS FOR GAMMA DOSE-RATE METERS

by

S. McGowan

PROJECT NO. SPN 11A20-4

MARCH 1982
OTTAWA

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CADMIUM TELLURIDE DETECTORS FOR GAMMA DOSE-RATE METERS

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Nuclear Effects Section
Protective Sciences Division

MARCH 1982
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ABSTRACT

The response of a 0.25-mm CdTe detector has been calculated for photon energies ranging from 0.06 to 5.0 MeV using the computer code CYLTRAN. Results show that the response is highly energy dependent, varying by almost three decades over this energy range. The response also depends significantly on the amount of scattering material adjacent to the detector. Some additional calculations show that the response can be made more uniform by using a lead/tin filter and by employing more than one energy-discrimination level, but good uniformity of response is difficult to achieve. At 2 MeV a response of 2.1×10^7 counts/(mm^2 gray) was found which is essentially the same as for silicon of equivalent thickness.

Measurements with a commercial CdTe detector confirmed the results of the calculations, although comparison of measured and calculated results indicated that the detector was not as thick as its specified 0.25 mm.

RÉSUMÉ

La réponse d'un détecteur CdTe de 0.25 mm a été calculée pour les énergies de photon allant de .06 à 5.0 MeV en utilisant le code en informatique CYLTRAN. Les resultats démontrent que la réponse varie fortement en fonction de l'énergie; jusqu'à trois décades au-dessus de cette plage d'énergie. La réponse dépend aussi de la masse de matériaux diffusants situés près de détecteur. Des calculs addionnels montrent que la réponse peut être plus uniforme en se servant d'un filtre de plomb et d'étain et en utilisant plus d'un niveau de discrimination d'énergie; néammoins une bonne uniformité de réponse est difficile à atteindre. A 2 MeV, la réponse obtenue était de 2.1×10^7 comptes/(mm^2 gray); ceci correspond à la réponse obtenue avec un détecteur au silicium d'une épaisseur équivalente.

Les mesures avec un détecteur CdTe commercial confirment les résultats des calculs. Cependant, la comparaison entre les résultats calculés et les résultats mesurés indique que l'épaisseur du détecteur est moindre que celle indiquée ci-haut.

TABLE OF CONTENTS

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1. INTRODUCTION

Cadmium telluride is one of a limited number of semiconductor compounds which can be produced in mm^3 volumes in relatively pure form. This along with its intrinsically high-energy band gap of 1.5 eV (compared with 1.1 eV for silicon), makes it suitable as a nuclear-radiation detector which can be used at ambient temperatures. It is, therefore, a promising detector for use in dose-rate instruments including military radiacmeters.

The potential and limitations of CdTe detectors are discussed by Siffert(1) and by Whited and Shieher(2). Practical applications of these detectors include use in medical probes (Meyer et al(3) and Garcia et al(4)), in radiation monitors at nuclear power stations (Jones(5)) and in a personal radiation chirper (Wolf et al(6)).

The high atomic numbers of cadmium (52) and tellurium (48) make CdTe particularly sensitive to low-energy gammas. Its photoelectric cross section increases sharply with reduction in photon energy as shown in Fig. 1, where comparison is made with the photon cross sections for silicon. As a result, the response of CdTe detectors is highly energy dependent. The energy response of a 0.25-mm-thick CdTe detector is examined here by computational methods, using the computer code CYLTRAN (see Ref. (7)), and by experimental measurements at a limited number of photon energies. The results of this investigation are useful in evaluating detectors of this material for use in instruments for dose-rate measurements.

2. METHODS OF CALCULATIONS

Calculations of the response of the CdTe detector follow the methods outlined in an earlier report (McGowan (8)) where the computer code CYLTRAN was used to calculate the response of silicon radiation detectors. In this case carbon of unit density is used as the electron-equilibrium layer surrounding the CdTe (see Fig. 2) as required for the calculations. Substitution of any other low-atomic-number material, such as a plastic, would have only a small effect on the calculated response.

Calculations were done at photon energies of 0.06, 0.08, 0.1, 0.15, 0.2, 0.3, 0.5, 0.7, 1.25, 2.0, and 5.0 MeV using the minimum thicknesses of the electron-equilibrium layer. For most of these energies, calculations were also made using thicker layers of carbon than are required for electron equilibrium, in order to study the effect of photon scattering from these layers. All calculations were made with the photons entering the detector normal to the main surfaces which are the ends of the short cylindrical detector.

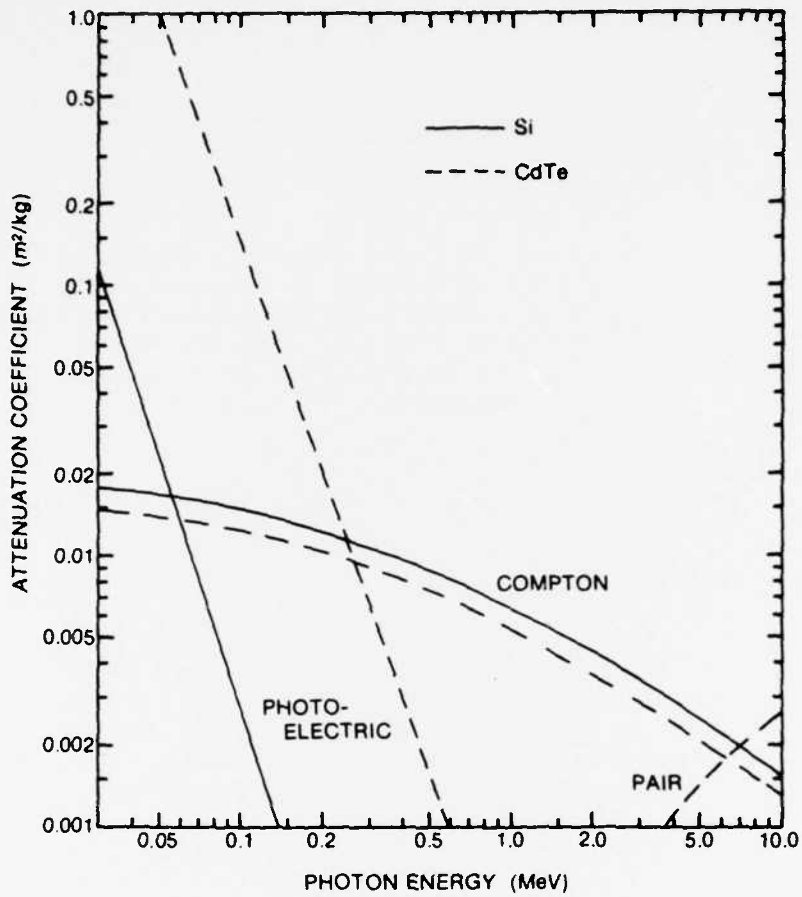

Figure 1. Photon attenuation coefficients for cadmium telluride and silicon. Note the much larger photoelectric coefficient for CdTe and the large energy dependence of this coefficient.

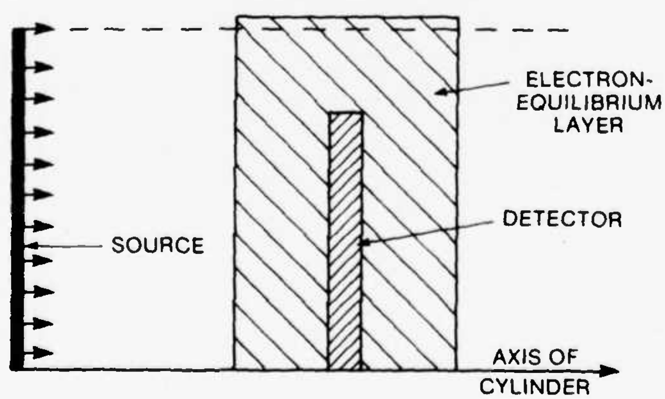

Figure 2. Cross section of one half of the problem cylinder for the computer code CYLTRAN used to calculate the detector response. For these calculations an electron-equilibrium layer of carbon surrounded the CdTe detectors.

3. EXPERIMENTAL METHODS

Two CdTe detectors of area 2 mm × 2 mm were obtained from Radiation Monitoring Devices, Inc. for test purposes. The specified thicknesses were 0.25 and 2.0 mm. The thinner detector was specified as a high-resolution detector and was found to have a full width at half maximum of 8 keV for the 59.5-keV gammas from ^{241}Am. The thicker detector, which was specified as a counter, was found to give no clearly defined photopeak, but gave pulse heights ranging from zero up to a maximum which, presumably, corresponds to the photopeak energy. Increasing the applied voltage increased the average pulse height without changing the maximum pulse height appreciably. It can be concluded that the pulse height is degraded by loss of charge carriers in this detector. While response of this nature may be adequate for many purposes, it is questionnable whether this response would be consistent from detector to detector. Most of the measurements made here are with the thinner detector where the pulse height appears to be directly proportional to the absorbed energy. This is, of course, the assumption which is made for the calculated response.

Pulse-height spectra from the detector output were recorded so that the response could be derived for any chosen cut-off energy. ^{60}Co, ^{137}Cs and ^{241}Am sources provided essentially monoenergetic gamma sources at 1.25, 0.662 and 0.0595 MeV, respectively. A ^{133}Ba source was also used with a principal gamma peak at 0.355 MeV. This isotope also emits several other gammas. The most prominent are at 0.081, 0.276, 0.303 and 0.384 MeV. The gamma-ray at 81 keV was eliminated by filtration with lead (7.5 kg/m^2) and tin (14 kg/m^2) leaving a source with an effective energy which is estimated to be about 0.34 MeV for purposes of measurements with the CdTe detector. Also, measurements were made using x-rays which were heavily filtered to give narrowed spectra with peak intensities at energies ranging from 70 to 250 keV.

4. RESULTS OF CALCULATIONS

4.1 PULSE-HEIGHT SPECTRA

Calculated pulse-height spectra from a 0.25-mm CdTe detector, surrounded by carbon of density 1 g/cm^2, are shown in Figures 3 to 6 for photon energies of 0.1, 0.2, 0.3, and 0.7 MeV. Spectra are shown for two thicknesses of the external layers of carbon to demonstrate the effect of photon scattering from the additional material.

Fig. 3 shows that at0.1 MeV almost all of the pulses are in the photopeak. A second peak which is observed 25 to 30 keV below the photopeak energy is due to the escape of the K x-rays of cadmium and tellurium from the detector Between these two peaks there is an appreciable number of pulses only for the detector with the thicker external layer. These pulses are due to the absorption in the detector of secondary photons from the external layers. Secondary Compton photons range in energy from 72 keV up to the primary energy of 100 keV. The Compton edge at 28 keV for the 0.1-MeV photons is barely discernible.

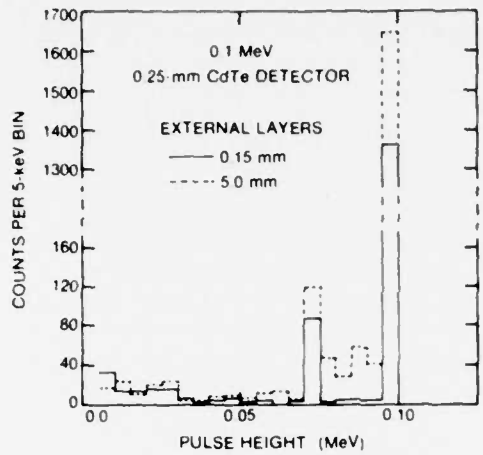

Figure 3. Calculated pulse-height spectra from CdTe detector irradiated by 0.1-MeV photons. Most of the counts are seen to occur in the photopeaks. The peaks between 70 and 75 keV are due to the escape of K x-rays from the CdTe. The larger photopeak for the thicker external layer (of 1 g/m² carbon) is due to a larger photon fluence having been used for that calculation, but most of the excess counts below the photopeak for the thicker layer are due to secondary photons produced in the larger external mass of carbon.

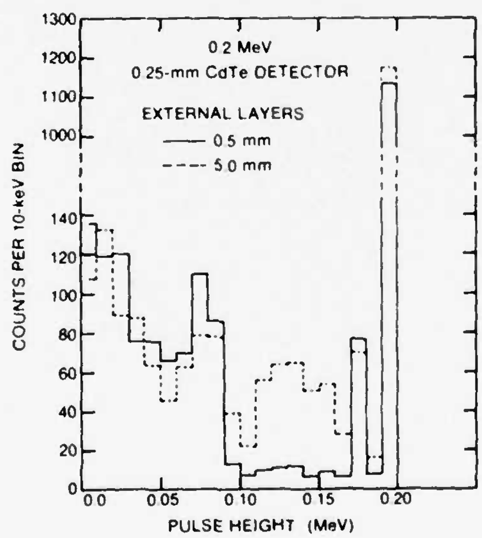

Figure 4. Calculated pulse-height spectra from CdTe detector irradiated by 0.2-MeV photons. In comparison with the 0.1-MeV spectra, the photopeaks are down but there is a larger fraction of counts due to Compton electrons below the Compton edge which occurs at 88 keV for 0.2-MeV photons. The larger number of counts between the photopeak and the Compton edge for the thicker external layer shows the effect of secondary photons from this layer. A slightly larger photon fluence has been used for the calculations with the thicker layer.

Fig. 4 shows that at 0.2 MeV, the photoeffect is still dominant but the number of Compton pulses seen below the Compton edge of 88 keV is significant. The effect of scattering from the thicker carbon layer is seen by the enhanced response, indicated by the dashed histogram, between 110 and 155 keV.

At 0.3 MeV the photoelectric and Compton effects each accounts for about one half of the pulses greater than 60 keV. The two histograms in Fig. 5 differ only by a slight enhancement, from the thicker carbon layer, of the pulses above the Compton edge of 162 keV.

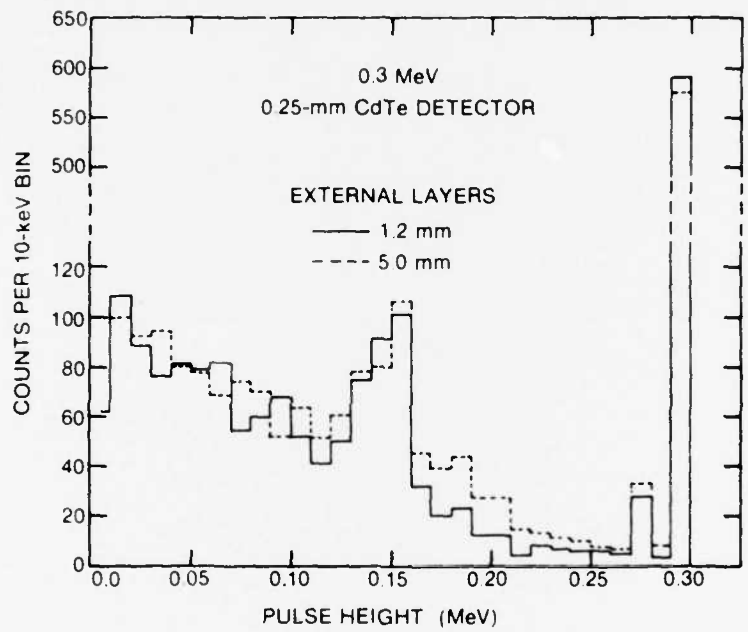

Figure 5. Calculated spectra from CdTe detector for 0.3-Mev photons. The number of counts below the Compton edge at 162 keV is approximately equal to the number in the photopeak for these spectra.

At 0.7 MeV the response is due primarily to the Compton effect though the photopeak is still clearly seen in Fig. 6. In this figure, the dashed histogram represents a detector surrounded by much thicker layers than for the three preceding cases discussed. A large increase in the relative number of pulses between 50 and 200 keV is seen as a result of the increase in thickness of the carbon layer. This enhancement appears to be greater than can be attributed to secondary gammas from the external layer and an explanation for the magnitude of this effect is given in Sec. 4.3.

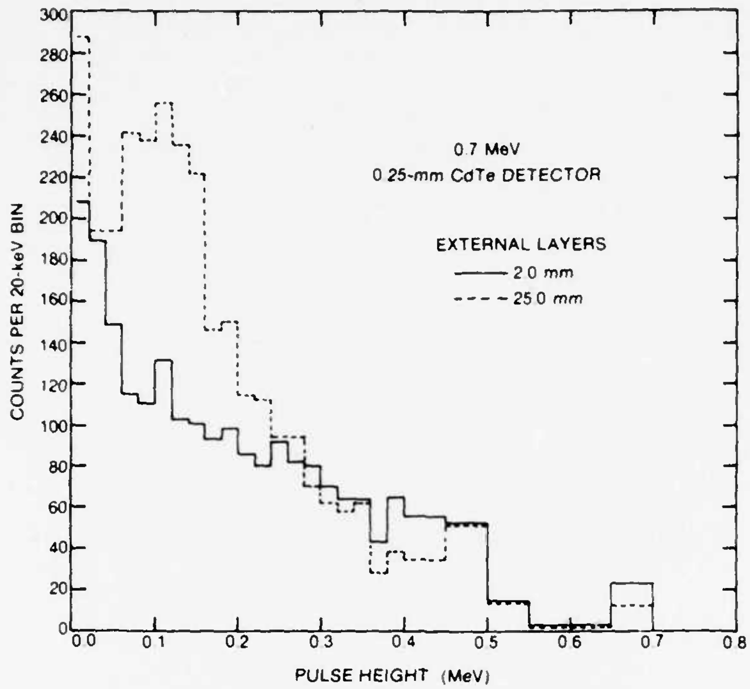

Figure 6. Calculated spectra from the CdTe detector for 0.7 MeV photons. At this energy most of the counts are due to the Compton effect. The photon fluence for the thicker layer was about one-half that for the thinner layer. A large increase in pulses at about 0.1 MeV is seen as a result of photons scattered from the 25-mm carbon layer, this layer being much thicker than for the spectra shown for the lower energies in figures 3 to 5.

The electron equilibrium layers used for 1.25 and 5.0 MeV were 5 and 27 mm, respectively. These are approximately the maximum electron ranges for the highest-energy Compton electrons from photons of these energies. At these energies, the photoelectric cross section for CdTe is much smaller than the Compton cross section so that most of the pulses are due to the latter effect. Thus, the 1-MeV pulse-height spectrum in Fig. 7 is essentially the same as for silicon (Ref. (8)) of equivalent thickness in terms of electron stopping power. The 0.25-mm thickness of CdTe is equivalent to about 0.54 mm of silicon. Most of the primary electrons are not completely absorbed in the detector and pulses heights are displaced toward lower energies in comparison to the spectrum of Compton electrons. However, there are considerable fractions of large pulses produced by these high-energy photons and it will be shown later that these can be employed for energy-response compensation.

At 5 MeV an appreciable fraction of the pulses in the detector is due to pair production as a result of the cross section as shown in Fig. 1. The peak in Fig. 7 below 200 keV corresponds to the energy lost by Compton and pair-production electrons which pass through the detector.

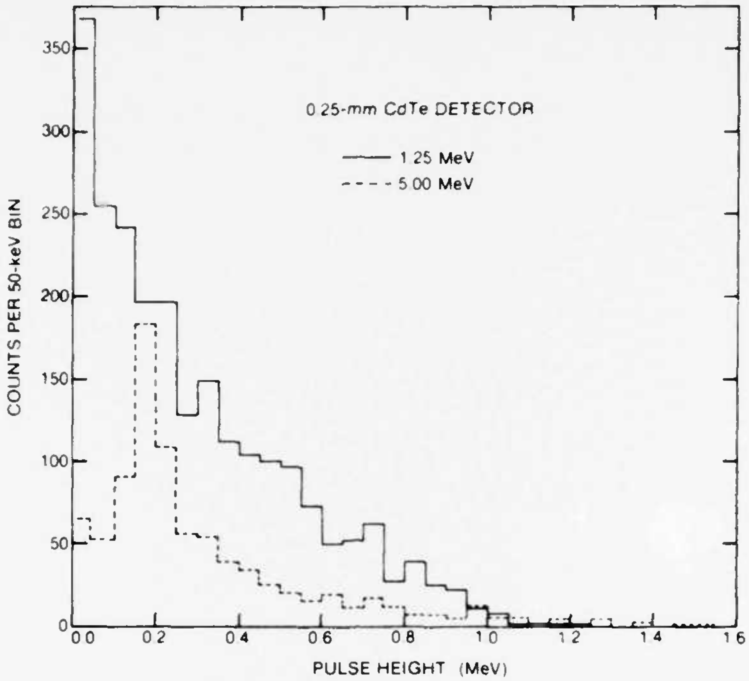

Figure 7. Calculated spectra from CdTe detector for 1.25- and 5.0-MeV photons using electron-equilibrium layers of 5 and 27 mm, respectively. Because the range of most of the primary electrons is much larger than the detector thickness, the pulse-height spectra fall well below the primary-electron energy distributions. The peak in the 5-MeV spectrum below 200 keV is produced by fast electrons which traverse the detector.

4.2 CALCULATED RESPONSE

The basic detector response is given in this report in terms of the number of pulses (above a selected discriminator level or cut-off energy E_c) per unit area and per unit kerma of soft tissue. Calculated responses for the 0.25-mm CdTe detector are tabulated in Table I for the eleven photon energies investigated and for values of the cut-off energy ranging from 60 to 400 keV. The radius of the detector and the thickness of the carbon layer surrounding the detector are also listed. The source, which is coaxial with the detector and which emits gammas parallel to the axis, was assigned a radius just less than that of the outer radius of the carbon as shown in Fig. 2.

As can be seen from Table I and Fig. 8, the response of this detector is highly energy dependent over the energy range of concern, varying by a factor of about 500 between 0.08 and 2.0 MeV. This behavior is, of course, expected because of the energy dependence of the photon absorption cross section of CdTe as mentioned earlier. Since the large photoelectric reponse persists above energies at which the Compton pulses exceed the cut-off energy of 60 keV in Fig. 8, the sharp minimum observed for the silicon detectors of Ref. (8) is not found for the CdTe detector.

TABLE I

Calculated Response of 0.25-mm Cadmium Telluride Detector as a Function of Photon Energy E_γ and Cut-Off Energy E_c. The Radius of the Detector and the Thickness of the Surrounding Layer of Carbon are also Listed. The Calculated Number of Counts above 0.06 MeV is Included as an Indication of Statistical Accuracy.

E_γ (MeV)	Radius (mm)	C-Layer (mm)	RESPONSE (10^7 counts/mm^2 gray (tissue)) E_c (MeV) = 0.06	0.08	0.10	0.15	0.20	0.30	0.40	COUNTS 0.06
0.06	1	2.0	1880*							1822*
0.08	1	0.1	1010							1356
0.08	1	2.0	998							1455
0.08	100	5.0	1009							1524
0.10	1	0.15	482	452						1474
0.10	1	2.0	497	460						1568
0.10	100	0.15	484	455						1557
0.10	100	5.0	524	475						1956
0.15	1	0.3	99.8	98.0	97.1					1558
0.15	1	2.0	102.7	100.9	98.8					1521
0.15	100	5.0	117.5	114.8	109.8					1441
0.20	1	0.5	35.2	31.2	28.9	27.8	25.7**			1760
0.20	1	2.0	35.9	32.5	29.8	27.8	26.0**			1527
0.20	100	0.5	38.4	35.0	32.9	31.1	29.2**			1445
0.20	100	5.0	42.5	39.0	36.3	30.5	26.7**			1868
0.30	1	0.35	10.74	9.25	8.31	6.16	4.74			455
0.30	1	2.0	11.19	9.93	9.06	6.28	4.90			761
0.30	100	1.2	12.02	10.88	9.82	7.22	5.62			1429
0.30	100	5.0	13.83	12.56	11.49	8.55	6.24			1560
0.50	1	1.2	4.56	4.17	3.84	2.99	2.46	1.11	0.52	603
0.50	100	1.2	4.73	4.30	4.04	3.19	2.44	1.16	0.55	1089
0.50	100	5.0	5.20	4.75	4.33	3.53	2.78	1.38	0.66	1009
0.70	1	2.0	2.98	2.81	2.60	2.21	1.75	1.12	0.67	429
0.70	100	2.0	3.15	2.96	2.76	2.29	1.86	1.15	0.64	1860
0.70	100	5.0	3.43	3.24	3.04	2.45	2.03	1.30	0.68	1147
0.70	100	25.0	5.38	4.85	4.38	3.06	2.20	1.15	0.62	1244
1.25	1	5.0	2.38	2.18	1.99	1.75	1.45	1.03	0.69	371
1.25	100	5.0	2.32	2.20	2.08	1.78	1.54	1.14	0.82	1899
2.00	100	10.0	2.13	2.03	1.94	1.72	1.46	1.06	0.77	907
5.00	100	27.0	2.46	2.41	2.34	2.06	1.50	0.99	0.70	802

* E_c = 0.055 MeV   ** E_c = 0.19 MeV

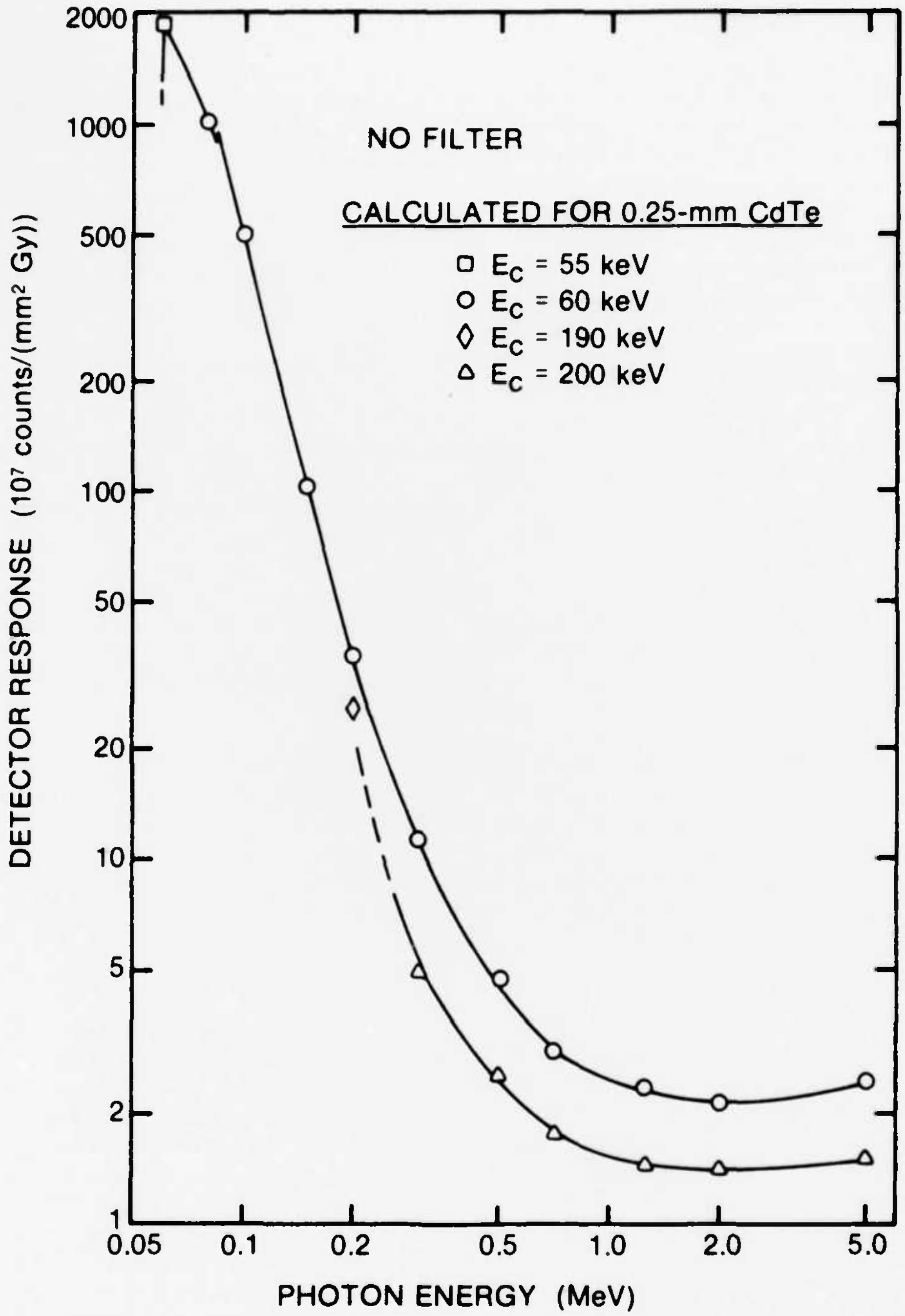

Figure 8. Response calculated for a 0.25-mm CdTe detector, adjusted for a 0.2-mm external layer of carbon of density 1 g/cm³.

Initially it was intended to do calculations for a 1-mm-radius detector which would correspond approximately to the 2 mm × 2 mm detector used experimentally. However, it became obvious that at the higher energies, where the radius of the outer carbon layer was much greater than 1 mm, the computer time required to get good statistical accuracy becomes prohibitive. Consequently, for the higher energies a detector of much larger radius (100 mm) was used, while calculations were made at the lower energies using both 1- and 100-mm radii. Increasing the detector radius from 1 to 100 mm is seen in Table I to increase the response by a few per cent at 0.08 and 0.1 MeV, by about 9% at 0.15, 0.2 and 0.3 MeV and by about 5% at 0.5 and 0.7 MeV. This increase can be attributed to photon scattering within the problem cylinder which includes the detector and the external layer of carbon. Enhancement of the response by photon scattering is discussed below in Sec. 4.3.

The effect of reducing the detector thickness was investigated by making a limited number of calculations with the 100-mm radius and minimum electron-equilibrium layers of carbon. For a 0.2-mm detector at 0.7 MeV, responses of 2.73, 1.56 and 0.46 (× 10^7counts/(mm^2 gray (tissue))) were found for E_c = 60, 200 and 400 keV, repsectively. In the same units, for a 0.15-mm detector, at 0.7 MeV values of 2.24, 1.07 and 0.25 were found for E_c = 60, 200 and 400 keV, while at 1.25 MeV responses of 1.73, 0.90 and 0.33 were measured at these discriminator levels. At these energies, the response is increasing approximately in direct proportion to thickness at E_c = 200 keV; it is less dependent on thickness at E_c = 60 keV and more dependent at 400 keV. At low energies, where only E_c = 60 keV applies and where most of the pulses originate in the detector, a directly proportionate relation between response and thickness is expected at this range of thickness.

The response of this detector is seen to be at a minimum at about 2 MeV, having a value of about 2.1 × 10^7 counts/(mm^2 gray) for E_c = 60 keV. Comparison with the calculated response of the 0.50-mm silicon detector of Ref. (8) shows that for equivalent thicknesses (0.25 mm of CdTe and 0.54 mm of Si) the sensitivity of these two materials is essentially the same. This is not at all suprising since the Compton effect dominates the cross sections of both these materials at this energy.

4.3 EFFECT OF PHOTON SCATTERING FROM EXTERNAL LAYERS OF CARBON

As can be seen in Table I, the response of this detector depends, to some extent, on the thickness of the external layer of carbon which surrounds it. Most of the photon interactions in the carbon are by the Compton process whereby the attenuation of the primary photons leads to the production of secondary photons of lower energy. Even when the response of Fig. 8 is translated to counts per photon, as in Fig. 9, there is an increase in response with decreasing energy below 0.7 MeV. Because of this, Compton scattering from the added carbon layer frequently leads to an enhancement of the response of the detector. Table I indicates an enhancement of about two per cent per mm (of carbon of density 1g/cm^3) for photon energies from 0.1 to 0.7 MeV.

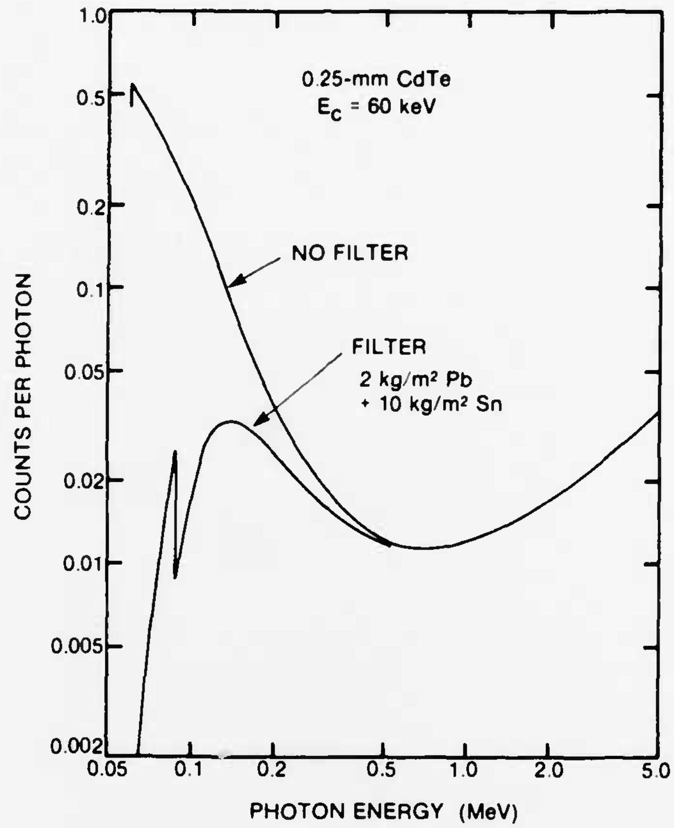

Figure 9. Calculated counts per photon for a 0.25-mm CdTe detector. The lower curve was obtained by applying the attenuation coefficients of lead and tin to the upper curve which was derived from the computer program. It can be appreciated from these relations, particularly with no filter, that an increase in counts will often result from degradation of photon energy by scattering.

Knowing the response as a function of energy, an estimate of the effect of external materials can be made from the scattered photon spectrum. The secondary photon spectrum is known from the Compton cross section, and scattered spectra are available from the CYLTRAN program which provides the spectrum of photons scattered out of the problem cylinder. The CYLTRAN-generated spectra agree closely with the Compton cross section (for generation of scattered photons) for cylinders having dimensions less than a few millimeters, but for cylinders with minimum dimensions exceeding a few centimeters a significant fraction of scattered photons are found below the energies of the secondary Compton photons. These must be tertiary photons produced by scattering of the secondaries in the carbon. Buildup of scattered gammas in thick layers, along with the relatively high response to the lower energies, can account for the relatively large number of pulses between 60 and 200 keV in the pulse-height spectrum from 0.7-MeV gammas (Fig. 6), when a 25-mm layer of carbon surrounded the detector.

The enhancement of response was calculated from Compton spectra and from computed, scattered-photon spectra, assuming that the total scattering per mm of carbon represented the scattering at the detector per mm or carbon surrounding the detector. As seen in Fig. 10 (a) the response enhancement, predicted from the Compton spectra with E_C = 0.06 MeV is less than the 2% per mm indicated in Table I, being a maximum of 1.4% at 0.2 MeV. At 2 and 5 Mev, the addition of carbon outside the detector reduced the response as a result of the reduction in counts per photon, seen in Fig. 9, as the energy is reduced from these primary energies by Compton scattering.

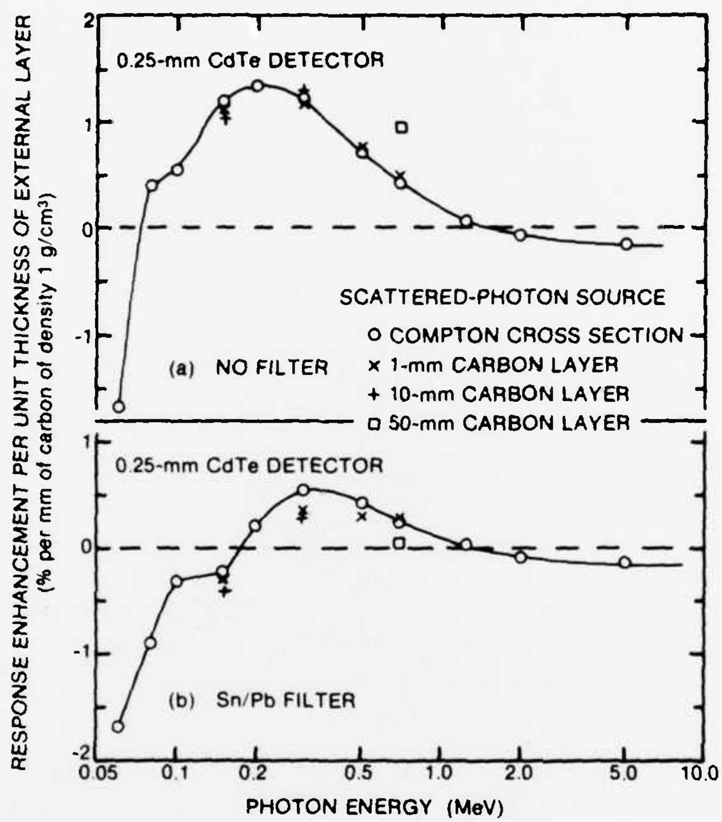

Figure 10. Calculated enhancement of detector response (for E_c = 60 keV) by the addition of external layers of carbon around the detector. Results were derived by applying the counts/photon relations of Fig. 9 to photon spectra generated according to the Compton cross section or according to the photon spectra scattered out of the problem cylinder from the CYLTRAN calculations. At 0.3-MeV, for example, the enhancement per unit thickness is seen to remain about the same over a fairly large range of thickness. Enhancement is seen to be reduced considerably by using the filter inside most of the external material.

Examples of the calculated response enhancement, in Fig 10(a), for 0.15, 0.3 and 0.7 MeV, using the scattered-photon spectra from the CYLTRAN calculations, show that approximately the same enhancement per mm of carbon is predicted for layers up to 10 mm in thickness as is predicted from the Compton spectra. The predicted enhancement is approximately doubled at 0.7 MeV when a 50-mm layer of carbon surrounds the detector.

Thus it can be seen from Table I and Fig. 10(a), that buildup of scattered photons from external materials can lead to considerable enhancement of the CdTe-detector response, and that, when used in this manner, the detector response depends appreciably on the amount of scattering material in the vicinity of the source and the detector.

4.4 IMPROVEMENT IN ENERGY RESPONSE BY FILTRATION

The very high response of the cadmium telluride detector at low photon energies can be reduced by filtration using high-atomic-number materials. Lead and tin which are commonly used to improve the energy response of Geiger tubes, are also convenient to use for CdTe. Because of the lead window below 88 keV. A filter, consisting of 10 kg/m^2 of tin and 2 kg/m^2 of lead, has been added, outside the equilibrium layer of carbon, to reduce the calculated response of Fig. 8 to that of Fig. 11. Excessive filtration leads to too great a reduction in reponse at low energies and, also, makes the low-energy response critically dependent on filter thickness. Thus, improvement by further filtration of this sort is limited. The variation in response with photon energy in Fig. 11 remains unsatisfactory and it is clear that simple filtration alone will not lead to an acceptably flat energy response.

The filtration provided by the lead/tin filter used for Fig. 11 has reduced the low-energy response considerably, thereby reducing the relative response to secondary and tertiary gammas to the point where the response enhancement by scattering materials outside this filter is much less important than for the unfiltered detector. Fig. 10(b) shows the enhancement in response which results from adding carbon outside the filter used in Fig. 11. This enhancement is seen to be well below that of Fig. 10(a), particularly when the 50-mm layer was used at 0.7 MeV.

4.5 IMPROVEMENT IN ENERGY RESPONSE BY UTILIZING THE PULSE AMPLITUDE

As can be seen from figures 3 to 6, there is a general increase in the average pulse amplitude over the energy range where the response is decreasing with increasing photon energy. Thus, incorporating the pulse amplitude into the response can be used to yield a modified response with a reduced variation with photon energy.

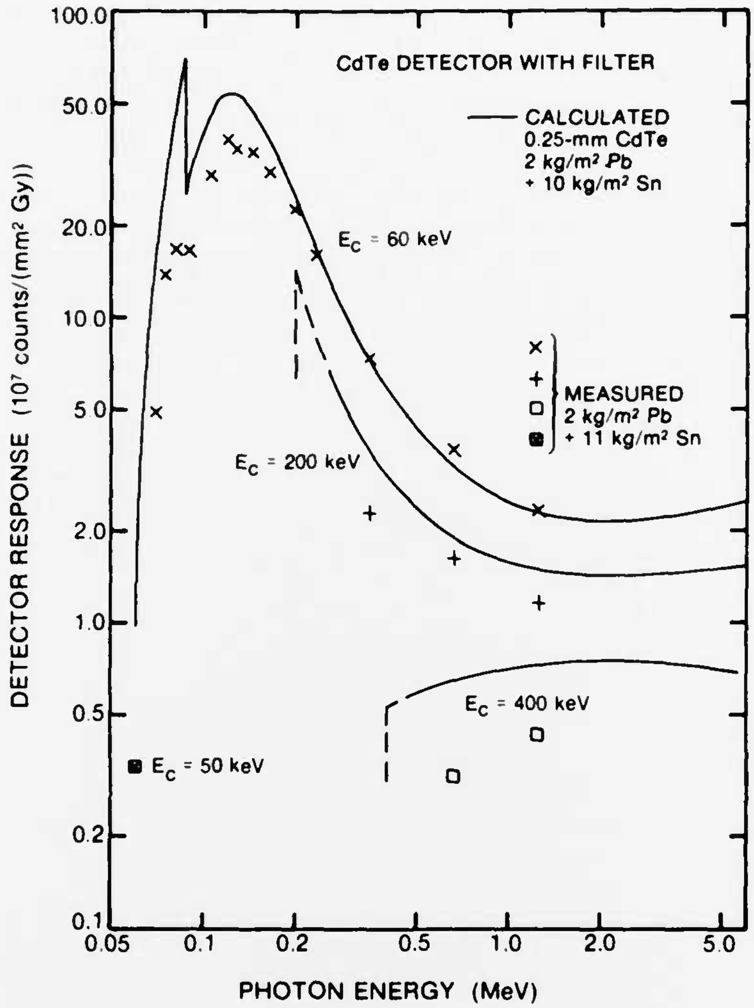

Figure 11. Calculated and measured response of CdTe detector with lead/tin filter. The attenuation coefficients of lead and tin were used to derive the calculated curves from those of Fig. 8. The measurements were made with a filter which was slightly thicker than used for the calculations. Comparison of the two measured points for E_c = 400 keV with the calculated response indicates that the commercial detector is between 0.15 and 0.20 mm in thickness in agreement with the indicated thickness at E_c settings of 60 and 200 keV.

Simply integrating the pulse amplitudes would give the dose absorbed in the detector. This would differ from the dose to tissue since the detctor material is not tissue equivalent, but would be more closely related to tissue dose than is the response measured by simply counting the pulses. As with the counting mode, pulse-height integration requires the use of a discriminator to reject detector noise pulses, so that only the portion of the pulse which exceeds the discriminator level can be included. A pulse-integration mode of this type is used in the radiation chirper of Ref. (6).

TABLE II

Average Absorbed Energy in Excess of 60 keV from Calculations with 0.25-mm CdTe Detector

$E\gamma$ (MeV)	Radius (mm)	C-Layer (mm)	$\overline{E - .06}$ (MeV)
0.08	1	2.0	0.0196
0.10	1	2.0	0.038
0.15	1	2.0	0.085
0.20	1	2.0	0.114
0.30	1	2.0	0.136
0.50	100	1.2	0.168
0.70	100	2.0	0.206
1.25	100	5.0	0.290
2.00	100	10.0	0.315
5.00	100	27.0	0.294

The average absorbed energy per pulse in excess of a selected cut-off energy $\overline{E - E_c}$ can be derived from computed spectra such as those in figures 3 to 7. $\overline{E - E_c}$ is listed in Table II as a function of photon energy $E\gamma$ for cut-off energy E_c = 60 keV. The product of $E - E_c$ and the responses of Fig. 8 and 11 give the modified responses shown in Fig. 12. Comparison of these figures shows that there is considerable improvement as a result of weighting the pulses in this manner, but even with the filter the modified response shows a factor of six difference between the values at 0.15 and 1.0 MeV.

A second method, which makes use of the pulse amplitude for energy compensation, uses the pulse-counting mode with more than one discriminator level and employs weighting factors which attach more importance to the pulses above the higher discriminator levels. Such a system using three discriminator levels, equivalent to E_c = 60, 200 and 400 keV, is shown in Fig. 13. The pulses which exceed 400 keV, N_{400}, are counted directly; those between 200 and 400 keV, $N_{200-400}$, are divided by 16; and those between 60 and 200 keV, N_{60-200} are divided by 64. The total output is given by

$$N_{out} = N_{400} + \frac{N_{200-400}}{16} + \frac{N_{60-200}}{64} \cdot \qquad (1)$$

Since $N_{200-400} = N_{200} - N_{400}$ and $N_{60-200} = N_{60} - N_{200}$,

$$N_{out} = \frac{60\, N_{400} + 3\, N_{200} + N_{60}}{64} \cdot \qquad (2)$$

Combining the groups of counts as in Eq. (2) is equivalent to combining the responses above the three values of E_c in Fig. 11. This gives the modified response proportional to N_{out} and shown in Fig. 14. While there is an improvement over all by using this modified response, the responses at specific energies are seen to differ considerably from the mean response. These can, of course, be reduced by using more discriminator levels at the expense of increasing the complexity of the readout circuitry. However, in practice where there is a broad spectrum of photon energies, these large variations in response will probably not be important.

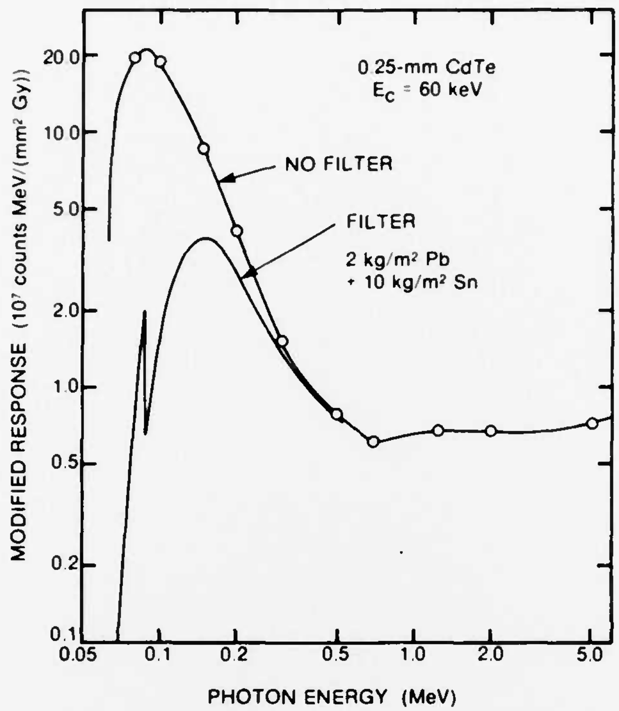

Figure 12. Modified response obtained by weighting the pulses in proportion to their energy in excess of the cut-off energy of 60 keV. The responses of figures 8 and 11 were multiplied by the average value of $E-E_c$ over the pulse-height spectra. The improved energy response is still not satisfactory.

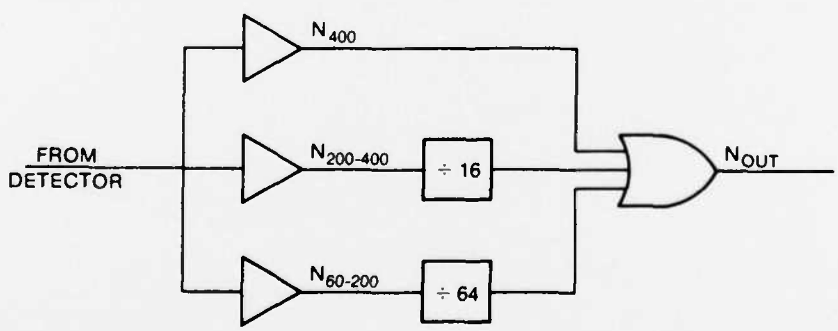

Figure 13. Block diagram of circuit for weighting the pulses from the detector to improve the energy response. N_{60-200} is the number of pulses of amplitudes between 60 and 200 keV, $N_{200-400}$ is the number between 200 and 400 keV and N_{400} is the number which exceed 400 keV.

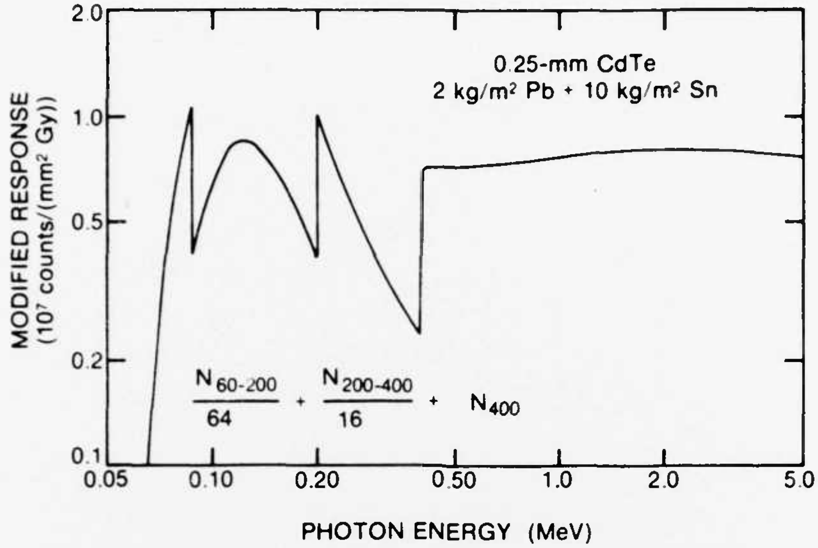

Figure 14. Compensated detector response obtained by dividing the number of pulses of amplitudes between 60 and 200 keV by 64 and that between 200 and 400 keV by 16 before adding to the number greater than 400 keV, as in Fig. 13. This is based on the calculated response curves of Fig. 11. The over-all response is fairly good but with extremes at the discriminator energies.

5. RESULTS OF EXPERIMENTAL MEASUREMENTS

Changes in the measured pulse-height spectra with gamma filtration indicated that there were appreciable fractions of counts due to backscattering from the ^{60}Co- and ^{137}Cs-source containers. Consequently, a filter (filter L) consisting of 18 kg/m^2 of Pb followed by 14 kg/m^2 of Sn was used at the apertures of these sources for most of the measurements. According to the attenuation coefficients of these materials, this filter should remove about 85% of the backscattered gammas, which have energies at about 200 keV from these sources, while reducing the number of primary gammas by less than 25%. In addition, the tin should attenuate any Pb x-rays, produced by scattering from the source containers and lead filter, to a few per cent.

The detector is potted within a cylinder of plastic 9 mm long by 6 mm in diameter and is located near the end of the cylinder which faced the sources. The two electrical leads emerge from the other end of the cylinder. Measurements were made both with and without a filter at the detector. This filter (filter K), which consists of 2 kg/m^2 Pb and 11 kg/m^2 Sn (almost the same as used for the calculations), surrounded the detector except for the narrow angle used by the electrical leads. The detector was operated with a reverse bias of 20 V. Increasing this to 25 V was found to result in a 3% increase in response to the ^{241}Am source.

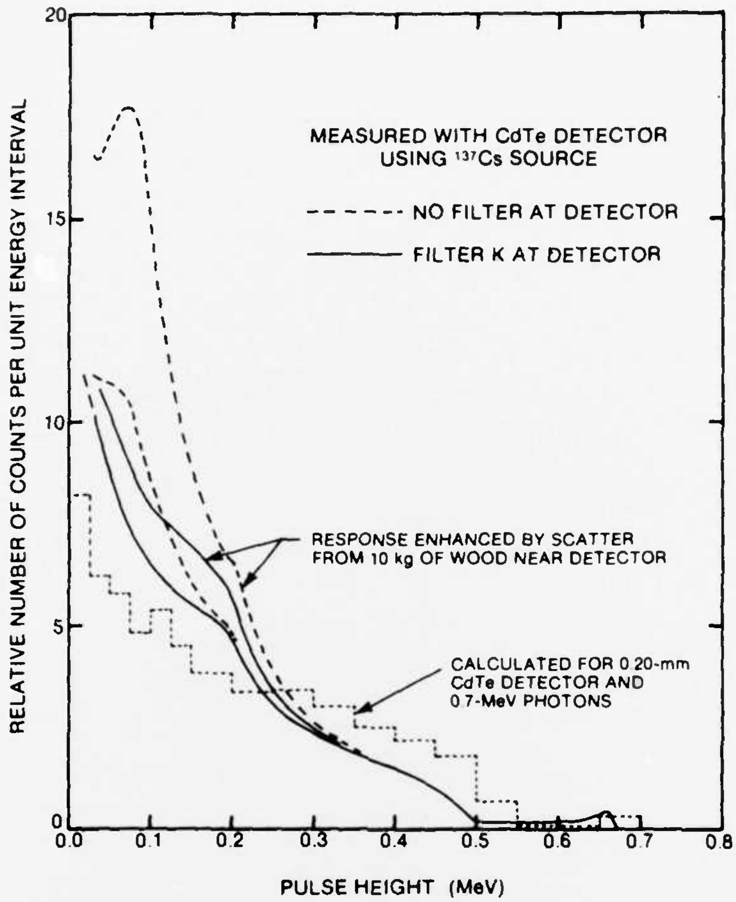

Figure 15. Measured spectra from the commercial detector exposed to the ^{137}Cs gammas. The photopeak at 0.66 MeV is clearly observed but most of the response can be seen to be due to the Compton effect. The reduction by the filter of the number of pulses below 0.3 MeV indicates the presence of scattered gammas of energy well below the primary energy. The number of lower-energy gammas is seen to be greatly increased by placing the scattering body of wood near the detector. Comparison of the measured spectra with the calculated spectrum for a 0.20-mm detector indicates that the commercial detector is thinner than that value.

Experimental spectra from the ^{137}Cs source are shown in Fig. 15. These measurements were made with filter L at the source with the object of reducing the fractional number of low-energy gammas produced by scattering in the source. The addition of filter K at the detector is seen to reduce the number of pulses between 50 and 200 keV, indicating the presence of some lower-energy gammas which are probably produced outside the source container. This reduction is very large when a scattering mass, such as the 10 kg of wood of Fig. 15, is added near the detector. This clearly demonstrates the dependence of detector response on the material adjacent to the detector, particularly when the filter is not used at the detector to filter out the low-energy scattered protons. Even with filters at both the source and the detector and no added scatterer, there may be a significant number of counts which can be attributed to scattered gammas.

Also shown in Fig. 15 is the calculated spectrum for a 0.20-mm CdTe detector from a 0.7-MeV photon source. The larger fraction of large pulses in the calculated spectrum, compared with the experimental spectra, indicate that the thickness of the detector used for the measurements is less than 0.20 mm. Note that 0.25 mm was chosen as the detector thickness for most of the calculations in this report, since that thickness was quoted by the manufacturer for the detector used for the measurements.

TABLE III

Measured Response of CdTe Detector

Photon Source	Source Filter	Source Energy Maximum (keV)	Source Energy Effective (keV)	Cut-Off Energy (keV)	Detector Response (10^7 counts/(mm^2 Gy)) No Filter	Detector Response (10^7 counts/(mm^2 Gy)) Filter K
^{241}Am	None		59.5	50	700	0.34
X-Ray	A	82	68	60	580	4.5
X-Ray	A	90	73	60	600	13.8
X-Ray	B	100	85	60	490	16.4
X-Ray	C	120	102	60	320	29.0
X-Ray	D	140	116	60	210	38.0
X-Ray	E	160	130	60	150	35.4
X-Ray	G	200	163	60	88	29.8
X-Ray	G	220	182	60		27.7
X-Ray	G	250	198	60	41.0	22.5
X-Ray	H	260	222	60		20.6
X-Ray	J	300	252	60	22.0	15.2
^{133}Ba	M		350	60	8.4	7.3
^{137}Cs	L		660	60	4.04	3.67
^{137}Cs	L		*	60		4.08*
^{60}Co	L		1250	60	2.39	2.33
^{60}Co	None		**	60	3.37**	2.60**
X-Ray	G	220	182	200		0.99
X-Ray	G	250	198	200	4.8	3.36
X-Ray	H	260	222	200		3.75
X-Ray	J	300	252	200		4.63
^{133}Ba	M		350	200	2.6	2.3
^{137}Cs	L		660	200	1.59	1.56
^{137}Cs	L		*	200		1.60*
^{60}Co	L		1250	200	1.17	1.17
^{60}Co	None		**	200	1.35**	1.18**
^{137}Cs	L		660	400	0.33	0.32
^{137}Cs	L		*	400		0.32*
^{60}Co	L		1250	400	0.45	0.43
^{60}Co	None		**	400	0.50**	0.44**

* Scattered Gammas Produced by 10 kg of Wood beside Detector
** Backscattered Gammas Produced by Source Container

Table III summarizes the results of response measurements for cut-off energies of 60, 200 and 400 keV. Filters A to J, used with the x-rays, refer to the filter set described by Jones and Benyon (9) who had measured the x-ray spectra which were used here. Filter M (7.5 kg/m^2 Pb plus 14 kg/m^2 Sn) was used to filter out the low-energy gammas from the ^{133}Ba source. The responses, measured using Filter K, are included in Fig. 11 for comparison with the calculated values for a 0.25-mm detector. For E_c = 400 keV, where there is very little contribution to the response by scattered gammas, the measured values at 0.66 and 1.25 MeV are well below the calculated values for the 0.25-mm detector. Comparison with additional calculations, done at 0.7 MeV for 0.15 and 0.20-mm detectors, indicate that the effective thickness of the experimental detector is between these two thicknesses. The same conclusion is reached by comparing the three experimental response points with calculated vales at E_c = 200 keV where scattered gammas make only a small contribution.

In light of the above conclusions, the seemingly excellent agreement between measured and calculated response for the higher photon energies at E_c = 60 keV is fortuitous, being the result of enhancement of response (by secondary gammas) of a detector which is thinner than the 0.25 mm used for the calculations. At the lower photon energies, enhancement by scattered photons does not compensate for the difference in response due to the experimental detector being thinner than 0.25-mm. Also, there may be significant attenuation by the copper lead, which extends in front of the detector, and by any inactive CdTe at the front of the detector.

From the experimental pulse-height spectra, a modified energy response was derived according to the formula of Eq. (1) Sec. 4.5. This is plotted in Fig. 16 using the effective x-ray energies from Ref. (9). The widths of the x-ray spectra have served to smooth out the experimental plot in comparison with the calculated energy response shown in Fig. 14, but the response for the

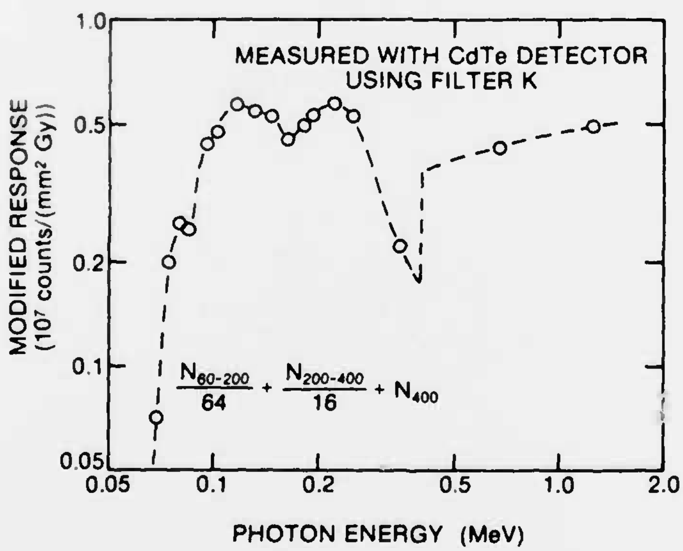

Figure 16. Modified response obtained from measured pulse-height spectra by weighting the pulses according to the energy groups defined by discriminators at 60, 200 and 400 keV. The interpolation in the region of 400 keV is made using the calculated curve in Fig. 14.

^{133}Ba source at 350 keV remains low as predicted by the calculations. The dashed curve above 350 keV has been interpolated using the shape of the calculated curve. As discussed above, the experimental points fall below the curve calculated for the 0.25-mm detector, presumably because the detector used was thinner than that value.

6. SUMMARY AND CONCLUSIONS

Calculations have been made of the response of a 0.25-mm CdTe detector to photons of energy ranging from 0.06 to 5.0 MeV using the computer code CYLTRAN. As expected from the photoelectric cross section for this compound, results show that the response is strongly energy dependent over this energy range. With a cut-off energy of 60 keV, the response falls from about 1.8×10^{10} counts/(mm^2 gray) just above the cut-off energy to 2.1×10^{7} counts/(mm^2 gray) at 2 MeV. The over-all response above 0.08 MeV can be improved considerably by using gamma filtration with tin and lead, for example, along with some mode of compensation based on the variation of average pulse height with photon energy. However, it would be difficult to achieve a response which does not differ at some discrete energy by more than 50% from the mean.

Because of photon scattering, which produces photons of lower energy at which the detector response is higher, the response was found to be enhanced considerably by the presence of materials adjacent to the detector, particularly at energies between 0.2 and 0.7 MeV. This effect was reduced by using a filter between the detector and the scatterer.

Measurements made with a commercial detector confirmed the general conclusions reached from the calculations. This detector was specified as having a thickness of 0.25 mm, but comparison of measured and calculated results indicates a thickness between 0.15 and 0.20 mm.

While this detector has a sensitivity which is very high indeed at the lower photon energies investigated, the response at these energies must be greatly reduced to achieve a response which is uniform over the energy range of interest in personal dosimetry. Thus, the sensitivity should be rated at the energies where it is a minimum, unless it can be shown that a large fraction of the dose is not delivered where the response is low or unless the detector is being used for relative measurements where the spectral distribution of photons is unchanged. At minimum response, this detector has essentially the same response as a silicon detector of equivalent thickness. On this basis the CdTe detector, therefore, offers no improvement in sensitivity over the silicon detector.

7. ACKNOWLEDGEMENTS

The calculations of this report are based on the computer code CYLTRAN developed at Sandia Laboratories. The author is grateful to the originators of this code and to the Radiation Shielding Information Center at Oak Ridge National Laboratory for making this code available.

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KEY WORDS

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GAMMA RAYS
DETECTORS
CYLTRAN COMPUTER PROGRAM

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13 ABSTRACT

The response of a 0.25-mm CdTe detector has been calculated for photon energies ranging from 0.06 to 5.0 MeV using the computer code CYLTRAN. Results show that the response is highly energy dependent, varying by almost three decades over this energy range. The response also depends significantly on the amount of scattering material adjacent to the detector. Some additional calculations show that the response can be made more uniform by using a lead/tin filter and by employing more than one energy-discrimination level, but good uniformity of response is difficult to achieve. At 2 MeV a response of 2.1×10^7 counts/(mm^2 gray) was found which is essentially the same as for silicon of equivalent thickness.

Measurements with a commercial CdTe detector confirmed the results of the calculations, although comparison of measured and calculated results indicated that the detector was not as thick as its specified 0.25 mm.

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