Development of Gamma-ray Monitor using CdZnTe Semiconductor Detector

A. H. D. Rasolonjatovo[1], T. Shiomi[1], T. Nakamura[1]
Y. Tsudaka[2], H. Fujiwara[2], H. Araki[2], K. Matsuo[2], H. Nishizawa[2]
[1]Cyclotron and Radioisotope Center, Tohoku University, 980-8578 JAPAN
[2]Mitsubishi Electric Corporation, JAPAN

INTRODUCTION

These days the CdZnTe (CZT) semiconductor detector is preferably used for X-ray and gamma-ray detection, because of its high efficiency and good energy resolution in use at room and higher temperatures. In this study, we aim to develop a new gamma-ray monitor using a $Cd_{0.5}Zn_{0.5}Te$ semiconductor detector. Nowadays, the silicon semiconductor detector is widely used as a sensor of the gamma-ray monitor, but the silicon detector has lower sensitivity to high energy gamma rays due to lower atomic number (Z=14) compared to the CZT detector (Z= 48 for Cd, 30 for Zn and 52 for Te) and decreases the sensitivity with the temperature above about 60° C. We therefore tried to get the gamma-ray monitor with higher sensitivity even in higher temperature which is realized in the power reactor core, for example, and at the same time to have a flat energy response within ±10% difference over the photon energy region from 10keV to 7MeV. At first, the photon energy response and the angular dependence of this monitor were studied by measurements and by calculations.

EXPERIMENTS

As a sensor, we used a $Cd_{0.5}Zn_{0.5}Te$ detector having 10mm x 10mm size by 2mm thickness (Fig.1).

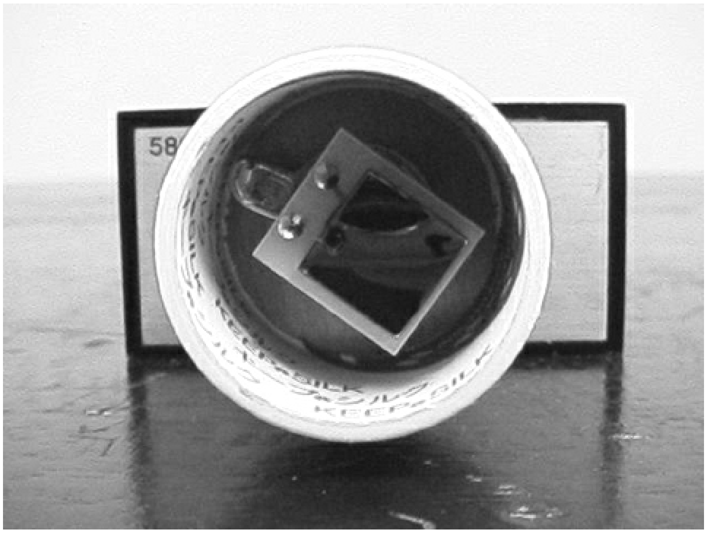


Fig.1. 10 x10 x2 mm^3 CZT detector

The detector was directly coupled to the low noise preamplifier (Model 850) fabricated by Clear-Pulse Co.Ltd. The bias voltage of +24 V to the detector was supplied from the regulated power supply PR 36-1.2 A fabricated by Kenwood. The preamplifier was connected to a linear amplifier ORTEC 571 with a 2μs shaping time. The detector and the preamplifier were covered with an Al foil of 0.015 mm thickness to decrease the electromagnetic noise.

In order to get the energy response of the CZT detector, the measurements were done using the mono-energetic X-ray beam sources from 10 to 40 keV and the radioactive photon sources of ^{241}Am (368 kBq), ^{57}Co (96 kBq), ^{137}Cs (418 kBq), ^{60}Co (372 kBq) and ^{88}Y (439 kBq) having photon energies of 59.541 keV to 1836.01 keV.

The experiments using X-ray beam sources were performed at a beam line of the Photon Factory of High Energy Accelerator Research Organization (KEK), Japan. The X-ray energy spectra and the absolute values of the X-ray fluence were measured respectively with the HP Ge detector and the free-air ionization chamber. In order to investigate the variation of the detection efficiency with the filters, we also measured the pulse height distributions of the CZT detector covered with the Al, Cu, Cd and Pb filters of various thicknesses. Figure 2 shows the schematic view of the experimental arrangement at a beam line of the Photon Factory at KEK.

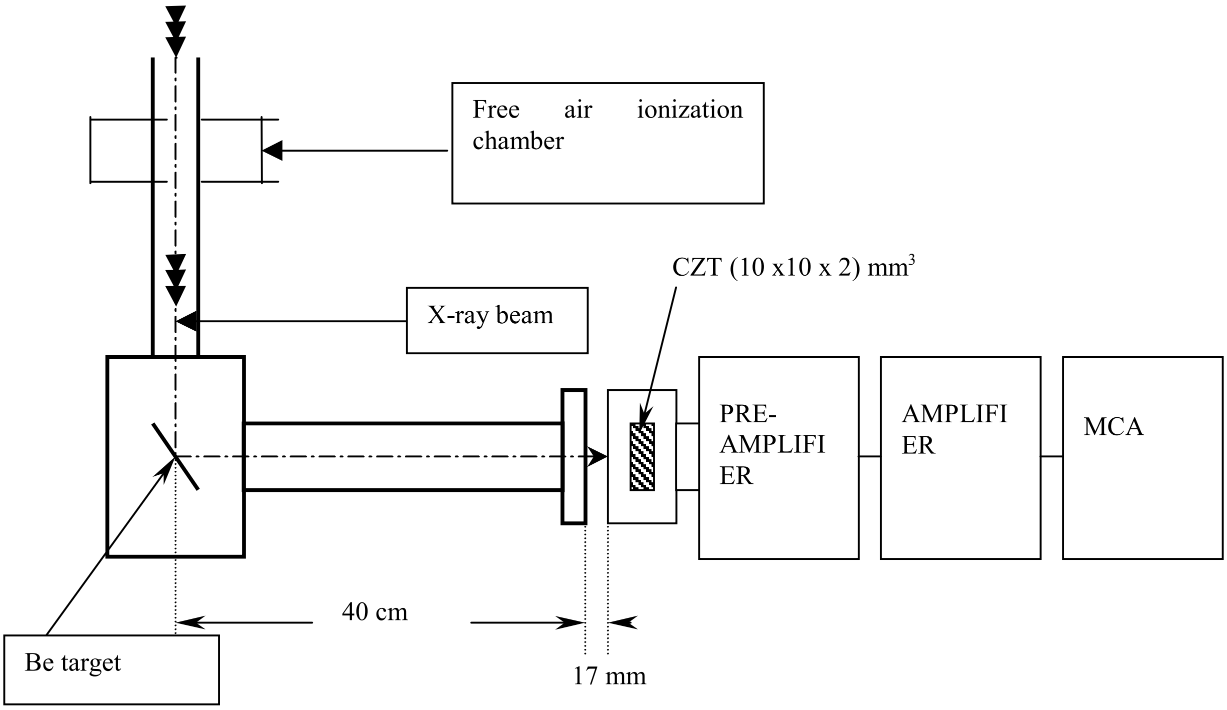


Fig.2. Experimental set-up at a beam line of the Photon Factory at KEK

The measurements using point sources were carried out at the Hot Laboratory of the Cyclotron and Radioisotope Center (CYRIC), Tohoku University, Japan. By setting a lead shadow bar of 80 mm long and 40mm diameter between the source and the detector, the contribution of the room-scattered photons was subtracted from the measured results. The fraction of backscattered photons was about 2%. The measurements using point sources were performed only for the non-filtered CZT, but in the directions of 0 to 90° by rotating the CZT detector in order to get its angular dependence. The ^{137}Cs source was covered with a 1mm thick Al foil to absorb the 661.65 keV conversion electrons from the electron capture reaction.

CALCULATIONS

The calculations of the pulse height spectra of the detector were performed with the electron-photon cascade Monte Carlo code EGS4 (1) with taking into account the carrier trapping effect (2). The charge collection of a detector is proportional to the product of the mobility and lifetime for electrons and holes; for the case of our detector the product $\mu\tau$ for electron is 3x10-3 $cm^2.V^{-1}$, and for hole $2x10^{-5}$ $cm^2.V^{-1}$. The energy needed to create an electron-hole pair is 4.43 eV (3). Three cases have been considered (2): energy absorption only; the drift distance of the carrier is constant; the drift distance of the carrier has an exponential distribution (2). The induced charge is calculated as follows:

$$If \quad \lambda_e > d, \lambda_h > d, \qquad Q(x) = \frac{E}{\varepsilon} e$$

$$If \quad \lambda_e > d, \lambda_h < d, \qquad Q(x) = \frac{E}{\varepsilon} e \left[\frac{d-x}{d} - \frac{\lambda_h}{d} \right]$$

$$If \quad \lambda_e < d, \lambda_h > d, \qquad Q(x) = \frac{E}{\varepsilon} e \left[\frac{\lambda_e}{d} - \frac{x}{d} \right]$$

Where λ_e is the mean free path of the electron, λ_h the mean free path of the hole, d the thickness of the detector, x the distance from the cathode to the interaction point, E the deposited energy and ε the energy needed to create an electron-hole pair.

From the comparison of the three cases with the experimental results, the exponential distribution of the drift distance of carriers was considered. When a trapping of electron-hole pair occurs, the full energy peak moves to lower energy (4). The shift in energy was about 20%.

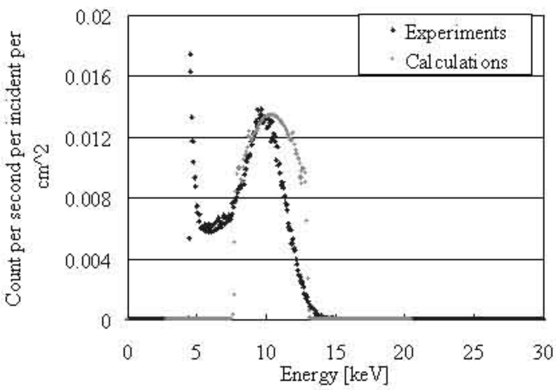
RESULTS AND DISCUSSIONS

1.Pulse height spectra

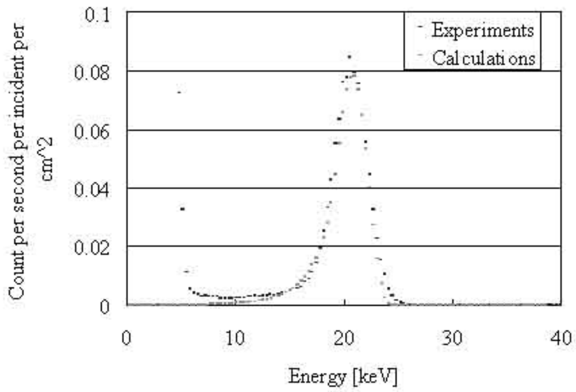
The output pulse height spectra were measured with the multi-channel analyzer. The noise level of the system was about 6 keV. The responses of the two photon energies of 1332.5 keV and 1173.24 keV for ^{60}Co and of 1836.01 keV and 898.02 keV for ^{88}Y, were calculated separately and were then added taking into account the branching ratio of each energy. For the case of ^{57}Co and ^{241}Am, only the respective 122.06 keV and the 59.541 keV photon energies have been considered in the calculations. Figure 3 shows the comparison of measured and calculated pulse height spectra of 10, 20 and 40 keV X-ray beams, ^{241}Am (59.541 keV), ^{57}Co (14.41, 122.06 and 136.47 keV), ^{137}Cs (30 and 661.65 keV), ^{60}Co (1173.24 and 1332.5 keV) and ^{88}Y (898.02 and 1836.01 keV). For 10, 20 and 40 keV, there can be seen single sharp photopeak. The full-width at half-maximum (FWHM) of the 10 keV photopeak is 4.4 keV, that of the 20 keV photopeak is 3.8 keV and that of the 40 keV photopeak is 4.3 keV. The measured pulse height distribution of the 40 keV X-ray presents two escape peaks at 10 keV from K_α X-ray of Te and at 14 keV from K_α X-ray of Cd. The lower energy peaks in the measured ^{241}Am spectrum result from the KX-rays at energies of 14 keV, 17.6 keV and 21.14 keV and the gamma-ray energy of 26.35 keV. These peaks do not appear therefore in the calculated response of the 59.54 keV gamma-ray. The peaks at 32 keV and at 36 keV are the escape peaks of K_α X-ray of Te and K_α X-ray of Cd, respectively. The FWHM of 59.54 keV peak is 5.8 keV.

For ^{57}Co, three photopeaks of 14, 122 and 136 keV can be seen in the measured spectra. The photopeaks of 122 and 136 keV are much broader than that of 14 keV. For ^{137}Cs, the $K_{\alpha 1}$-X-ray peak at 30 keV can be seen. For higher energy of 662 keV, the photopeak becomes very low. For 1173 and 1333 keV photons of ^{60}Co and 898 and 1836 keV photons of ^{88}Y, no photopeaks can be seen in Fig.3. This is because the charge collection efficiency degrades and the energy loss in the detector is dominated by the Compton scattering with the increase of photon energy. One can also notice that the increasingly high counts at low energy can be seen in the measured pulse height spectra of ^{60}Co.

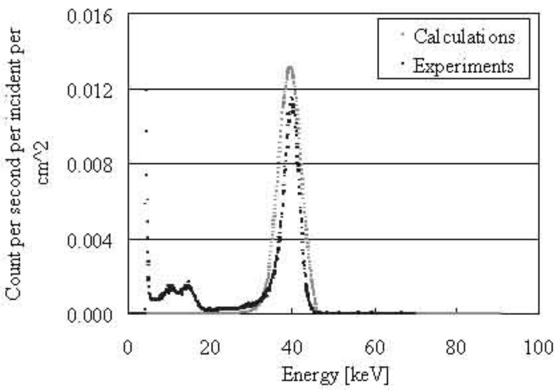
The agreement between the measured and calculated pulse height spectra is very good in general



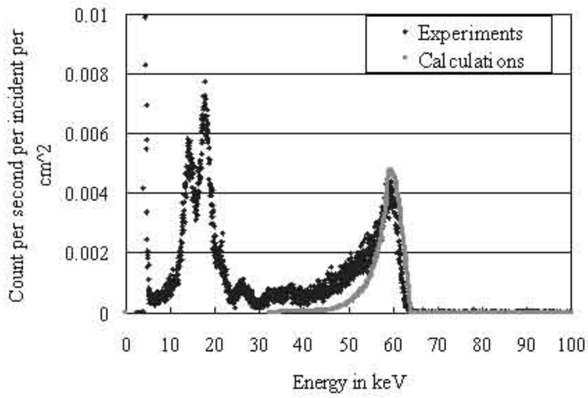
(a) 10 keV X-ray



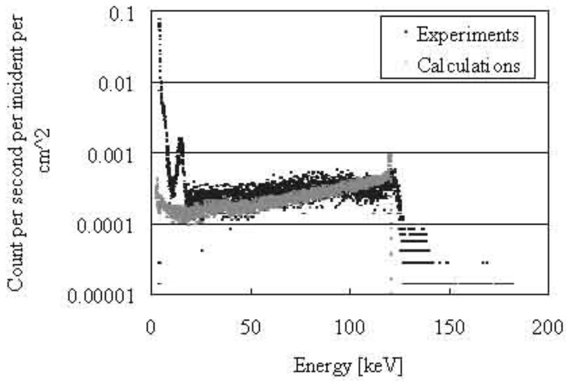
(b) 20 keV X-ray



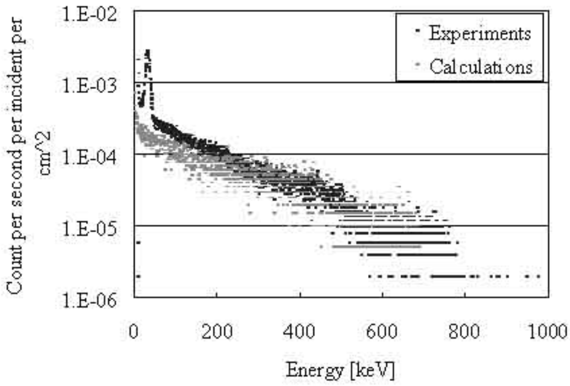
(c) 40 keV X-ray



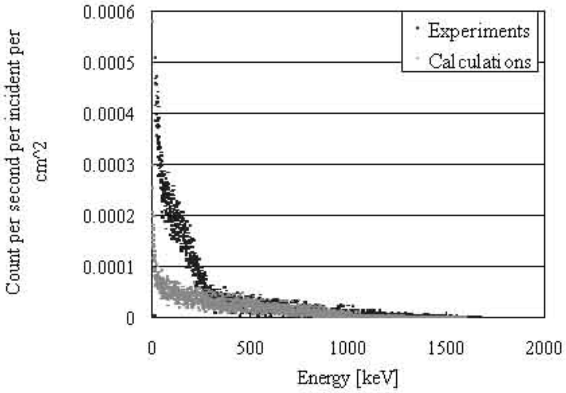
(d) ^{241}Am photon source



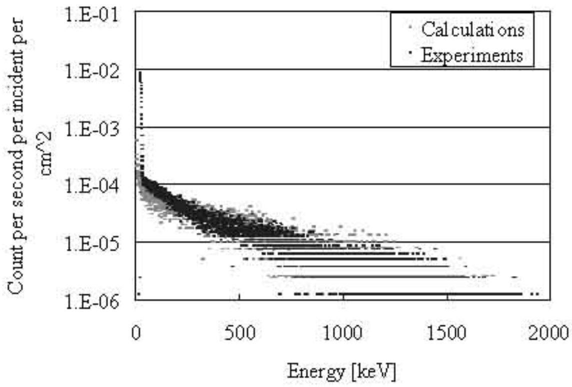
(e) ^{57}Co photon source



(f) ^{137}Cs photon source



(g) ^{60}Co photon source

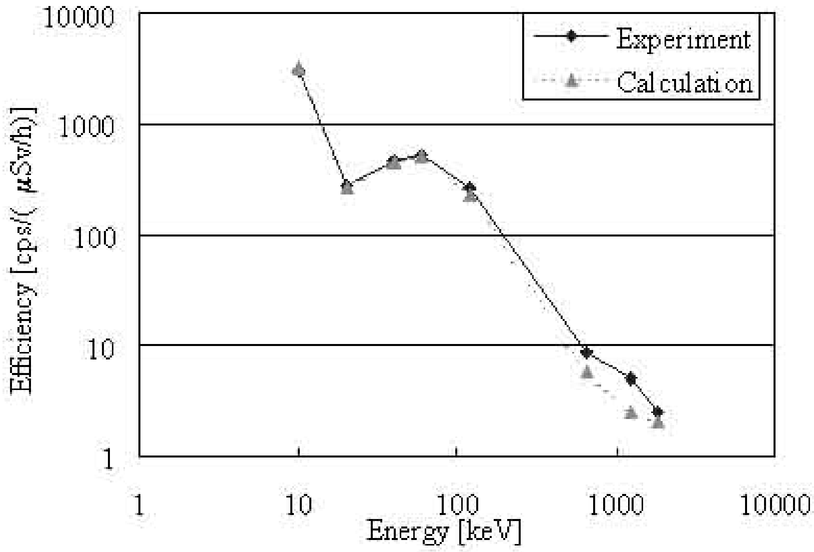


(h) ^{88}Y photon source

Fig.3. Comparison of measured and calculated pulse height spectra

2.Energy response

The efficiency of the 10 x 10x 2mm^3 CZT detector for photon energy range from 10 keV to 1836.01 keV is shown in Fig.4. For the conversion of fluence to dose equivalent, the conversion factor given by ICRP Publ.51 (5) is used. The measured and calculated efficiencies were obtained by summing the measured and Fig.4.



Efficiency of the CZT detector for a cut-off energy of 6 keV

calculated pulse height spectra by fixing the cut-off energy at 6 keV. But for ^{241}Am the subsidiary peaks from X-ray and the 26.35 keV gamma ray were not considered and the peaks of 14 and 136 keV gamma rays of ^{57}Co and 30 keV X-ray of ^{137}Cs were also excluded from the measured results in the efficiency estimation. The agreement between experiment and calculation is generally good, but for ^{137}Cs and ^{60}Co gamma rays the measured results are 32 and 51% higher than the calculated results. This difference results from the fact that the counts in the experiment are very high at low energy around the cut-off energy fixed to 6 keV. The efficiency is high for 10 keV and rather flat from 20 keV to 120 keV, and rapidly decreases with energy.

3. Angular dependence of the 10 x10 x 2 mm3 CZT detector

Figure 5 shows the angular dependence of the efficiency of the CZT detector using radioactive photon sources for 6 keV cut-off energy. Solid lines represent the measured results and the dotted lines are the calculated

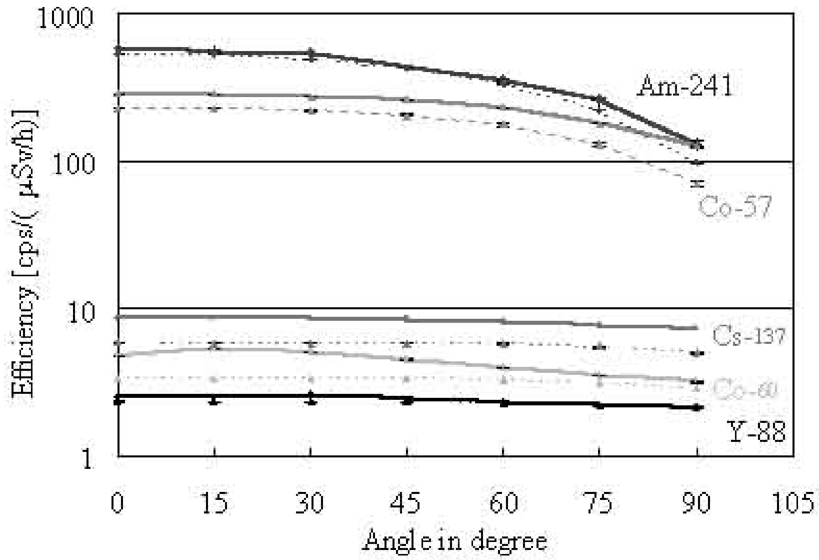


Fig.5. Angular distribution of the 10 x 10x 2mm^3 CZT detector efficiency from experiments and calculations

results. The angular distribution of the efficiency is almost constant for ^{137}Cs, ^{60}Co and ^{88}Y in the directions of 0 to 90°, but for lower energy photons of ^{241}Am and ^{57}Co, the efficiency decreases beyond 60°. The difference between experiment and calculation is about 9% for ^{241}Am, about 20% for ^{57}Co, about 32% for ^{137}Cs, about 41% for ^{88}Y and about 51% for ^{60}Co. This difference may come from the inclusion of noise counts due to low cut-off energy of 6 keV as described before. These results revealed that this CZT detector has an almost isotropic efficiency in the forward hemisphere.

4. Effect of various filters

Figure 6 shows the variation of the efficiencies for 10, 20 and 40 keV X-rays with various thickness (in mm) of the filters of Al, Cu, Cd and Pb. The cut-off energy was also fixed at 6 keV. The variation of the pulseheight is significant at 10 keV but is scarce at 40 keV when using an Al filter. To realize a flat response between 10 to 40 keV it is better to use an Al filter of 0.2 to 0.5 mm thickness. For Cu filter the thickness of 0.01 mm to 0.05 mm is recommended to have the flat energy response. Cd filter is quite interesting because the efficiency varies constantly at 20 and 40 keV whatever the thickness of the filter is. Lead is too much absorbent to be used at these low energies.

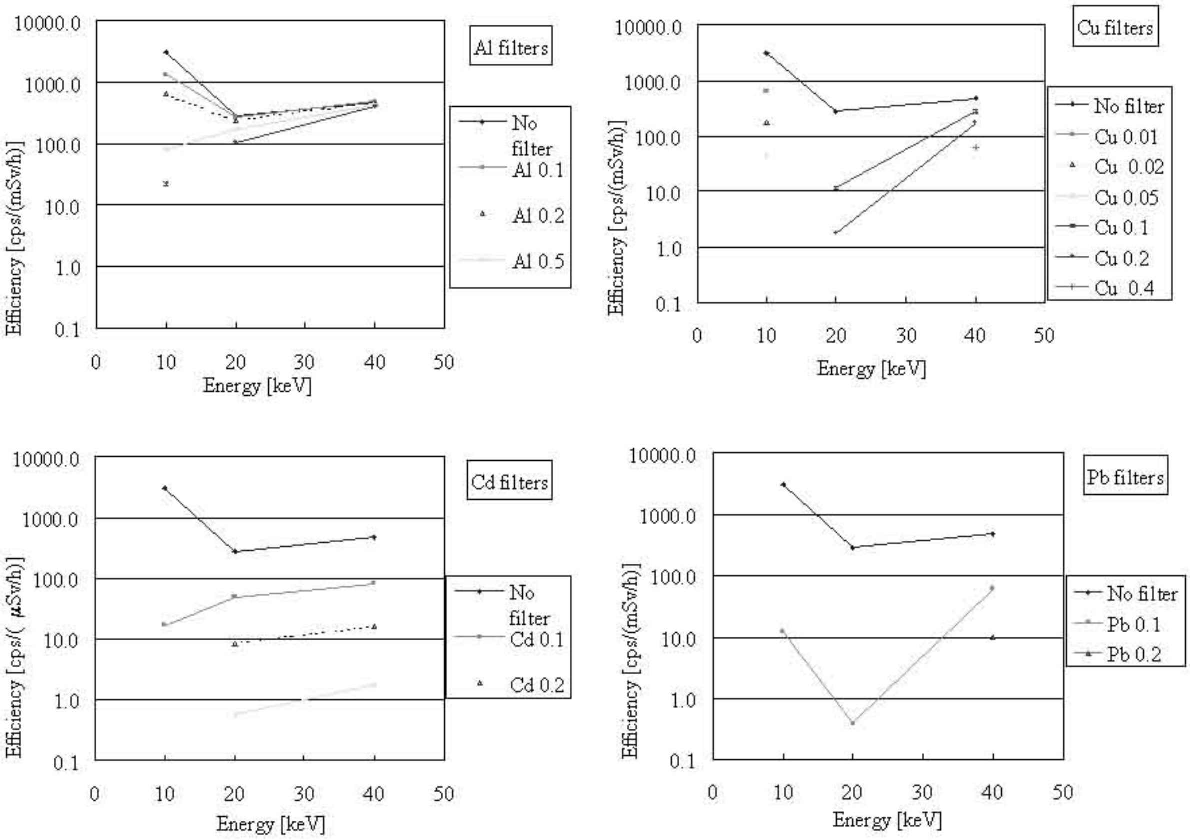


Fig.6. Variation of the efficiency with filters for 10 keV, 20 keV and 40 keV X rays by measurements

CONCLUSION

In this study, the pulse height spectra and the efficiencies of the CZT detector are given by experiment and calculation. The agreement between the experiment and the calculation is rather good. The variation of the detector response with the cut-of energy and with various filters was also obtained. We are now investigating to get the flat energy response in the energy range of 10 keV to 7MeV by combing these results.

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