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Non-linearity effects in the response of cadmium telluride nuclear radiation detectors

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Non-Linearity Effects in the Response of Cadmium Telluride Nuclear Radiation Detectors

by

J.A. Hodgkinson*, J.H. Howes and D.H.J. Totterdell

Abstract

An investigation has been made of the count-rate response of several CdTe detectors, to dose-rates in the range 0.1 rad/hr to 80 rad/hr. The relationship was found to be non-linear and it is suggested that this is due to a reduction in the depletion layer thickness resulting from the trapping of charge carriers. Over a limited range of dose-rates the relationship is of the form $C = KD^n$, with a mean value of n of 0.77 ± 0.03. This value is consistant with the limits of n of 0.67 and 1, predicted by a model proposed for the reduction in depletion layer thickness.

Radiation induced polarization was also observed but is thought not to be the cause of the non-linear response.

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Introduction

Cadmium telluride (CdTe) detectors prepared from high resistivity material have been widely used for gamma radiation measurements(1,2,3,4,5). The majority of these applications involve the use of these devices as room temperature gamma-ray spectrometers(1,2,3). Difficulties are experienced in producing detectors with the good charge collection characteristics necessary for high resolution X and γ-ray spectroscopy. This is particularly the case for the large thickness detectors required for high energy gamma radiation measurements.

Devices which are not of spectrometry grade are much easier to produce and are quite suitable for use as detectors of gamma radiation(6). The high Z, small size and ambient temperature operation of these detectors make them particularly suitable for the remote monitoring of high gamma radiation levels. One application involves the monitoring of highly active areas with a dose-rate range of 0.1 rad/hr to 100 rad/hr. The average energy of the gamma radiation is about 0.6 MeV and therefore rather thick CdTe crystals are required to give better sensitivity at the higher gamma-ray energies. It is necessary to know how CdTe devices behave at high gamma-ray dose-rates. In this paper we have described the results of an investigation into the response of several CdTe detectors to gamma radiation dose-rates covering the above range.

Detector Construction and Characteristics

The detectors were prepared from chlorine compensated p-type material grown by the **Travelling Heater Method (THM) [supplied by B. Lunn of the Crystal Growth Group, The University of Hull].**

An MOS structure was used for the contacts, consisting of a 100Å layer of germanium oxide onto which is deposited a palladium electrode. Gold wire (50 microns diameter) is bonded to the electrodes using a cold welding process incorporating an indium pad. The positive electrode is made smaller in area than the negative electrode, to improve the electron collection.

Planar and truncated hemispherical geometries were employed with thickness of 2mm and volumes of approximately 30mm^3 (planar) and 15mm^3(hemispherical). The resistivities as measured by the Van der Pauw technique(7), were between $5 \times 10^6 \Omega$ cm and $7 \times 10^7 \Omega$ cm. The detectors with the highest resistivity were the only ones having an adequate energy resolution to enable the escape peak of the 122 keV (^{57}Co) gamma-ray to be resolved. The photopeak-to-escape peak ratio method(8,9) was used to obtain a value of $5 \times 10^4 \Omega$ cm for the apparent or "nuclear" resistivity(9) of these detectors.

The detector leakage currents were typically 10nA at 200V.

All but two of the detectors showed strong polarization effects, as is characteristic of chlorine compensated CdTe. The detectors were allowed to stablize with the bias voltage applied before measurements were made.

Experimental

A 1.5 Ci ^{137}Cs gamma source (energy 0.67 MeV) was used to give exposure dose-rates from 0.1 rad/hr to 80 rad/hr, by varying the distance from source to detector. The dose-rates had previously been measured using a calibrated ion chamber.

The detector was connected via a charge sensitive preamplifier to a standard counting system and the count-rate measured using a discriminator threshold sufficient to eliminate electronic noise.

The system dead time was 100ns so that counting losses would not be significant for count-rates less than 10^5 s^{-1}.

Dose-Rate Response

The variation of the count-rate (C) with dose-rate (D) is shown in Fig. 1, for several detectors at a fixed bias voltage. Fig. 2 shows the effect of bias on the detector response. It is apparent from these curves that the response is non-linear but a better measure of the deviation from linearity is given by considering the variation of the ratio $\frac{C}{D}$ with dose-rate (Figs. 3 & 4). A marked deviation from linearity is a feature of the response of all these detectors even at quite low dose-rates.

The possibility of amplifier saturation was investigated and found to be significant only at count-rates above 3×10^4 s^{-1}. Adjustment of the amplifier time constants produced a small reduction in the non-linearity of the response at high count-rates but no improvement in the linearity was observed at lower count-rates.

Relationship Between Count-Rate and Dose-Rate

A plot of log C against log D for several detectors at a bias of 100V, is shown in Fig. 5. The graphs are approximately linear over most of the range with some tailing off at low dose-rates and high count-rates. The latter being a consequence of the amplifier saturation.

The straight line region of the graphs indicates a relationship of the form:

$$C = KD^n, \qquad (1)$$

where K is a constant for a given detector under fixed bias conditions and n is an integer.

The mean value of n obtained for the detectors at 100V bias (Fig. 6) is 0.77 ± 0.03.

There is some evidence that the value of n does vary slightly with the bias voltage.

Dose-Rate Polarization

It was observed that when those detectors exhibiting polarization were exposed to the higher dose-rates, the count-rate decreased from its initial value over a period of a few minutes (Fig. 7). The time constant of this variation was ~ 10^2s. This phenomenon was observed even though these detectors had been allowed to stabilize with the bias applied in the absence of radiation, prior to taking measurements. Apparently the high dose-rates induce a further polarization of these detectors. Similar dose polarization has been reported(10) and appears to be the result of an increase in the space charge caused by the trapping of electrons. On reducing the dose-rate, depolarization took place i.e., the count-rate returned to the normal value appropriate to that dose-rate (Fig. 8). The time constant of this recovery depends on the value of the final dose-rate and on the dose-rate to which the detector was previously exposed.

Care was taken in the measurement of the variation of count-rate with dose-rate (as outlined in the previous section), in order that the results were not affected by dose polarization or depolarization phenomena.

Discussion

The non-linear response of the CdTe detectors used in this work, corresponds to a reduction in the counting efficiency with increasing dose-rate. This could be the result of:-

(1) a reduction in the sensitive volume of the detector,

(2) a modification of the electric field leading to a reduced collection efficiency, or possibly,

(3) a change in the trapping and/or detrapping parameters caused by the high density of free charges.

The latter, in itself could produce a change in pulse height and therefore a shift in the spectrum, but would also affect both the electric field and the sensitive volume.

An attempt was made to characterize the detectors using the transient charge technique(11, 12,13), with a view to observing any changes in the mobilities, trapping and detrapping times resulting from an increase in dose-rate. Although it was observed that the time constant of the slow component of the transient pulse was decreased by a factor of 2 on exposure to 80 rad/hr, no firm deductions could be made and it was considered that the technique was unsuccessful because of the non-uniform electric field existing in these detectors(14). The latter was a consequence of the asymmetric electrode configuration and the fact that the detectors could not be fully depleted.

No significant change in the pulse height on exposure to high doses was recorded, whereas to account for the deviation from linearity a very large shift in the pulse height spectrum would be required. It seems probable therefore, that a reduction in the sensitive volume resulting from a decrease in the depletion layer thickness, is responsible for the observed non-linearity.

This theory is supported by measurements made of the capacitance of the detectors at low frequency(15) (100-400 Hz), where an increase in capacitance was observed on exposure to radiation. This was found to be the case even for those detectors not exhibiting dose polarization and therefore cannot be attributed to this phenomenon alone.

A reduction in the depletion layer thickness would accompany an increase in the space charge resulting from the trapping of charge carriers(10,16).

Hofstadter's model(10,16) gives a relationship between the depletion layer thickness x and the number of trapped charge carriers, N as:

$$x = \left(\frac{2E\ V}{Nq}\right)^{\frac{1}{2}} \qquad (2)$$

where V is the applied bias.

The count-rate (C) is related to x and the dose-rate (D) by:-

$$C \propto \mu x D \qquad (\text{for } \mu x \ll 1) \qquad (3)$$

where μ is the absorption coefficient.

If it is assumed that the number of trapped charge carriers is proportional to the rate at which charge carriers are generated, then it follows from (2) and (3) that:

$$C \propto D^{2/3} \tag{4}$$

$$\text{or} \quad C = KD^{0.67} \tag{5}$$

Although the Hofstadter model was developed for insulators for which there is no depletion layer in the absence of trapping, the same result may be obtained for a semi-conductor with a net ionized impurity concentration $|N_A - N_D|$, giving a depletion layer thickness:-

$$x = \left(\frac{2E\ V}{q|N_A - N_D|} \right)^{\frac{1}{2}} \tag{6}$$

Let the depletion layer thickness in the absence of trapping be x_i and suppose that if trapping takes place the thickness reduces to x_f.

If a small increase in ionized impurity concentration (dN) due to trapping, is assumed to be proportional to a small increase in the rate of production of charge carriers then:-

$$dN \propto x\ dD \tag{7}$$

where dD is the increase in the dose-rate.

It follows from (2), (6) and (7) that x_i and x_f are related by:

$$\frac{1}{x_f^3} - \frac{1}{x_i^3} \propto D \tag{8}$$

In the limit when $x_f \ll x_i$, this gives, as before:

$$C = KD^{0.67}$$

This result follows from the fact that when the trapped charge is large compared with the ionized impurity concentration, the model reduces to that of Hofstadter. However it can be seen from the above theory that as the assumption becomes invalid the power index (n) increases, becoming equal to 1 for the other limit i.e., $x_f = x_i$. It is therefore of interest to note that the measured value of n is within this range.

Any reduction in the depletion layer thickness which does take place must occur very rapidly, much more rapidly than in the case of the dose polarization (which can also be attributed to trapping). These two phenomena may therefore result from different mechanisms or from the same mechanism involving different trapping levels.

Further investigations are required to establish with certainty that a reduction in depletion layer thickness does occur, and to determine the mechanisms involved.

Conclusion

The response to dose-rate of the CdTe detectors used in this work, was found to be non-linear. In the dose-rate range 1 rad/hr to 40 rad/hr, the relationship between count-rate and dose-rate is of the form $C = KD^n$, where n has a value of 0.77 ± 0.03. This value is consistant with the limiting values of n ranging from 0.67 to 1 as predicted by a theory which postulates that the non-linearity is due to the trapping of charge carriers leading to a reduction in the depletion layer thickness.

The non-linearity does not appear to be the result of poor charge collection characteristics since detectors with resolutions ~ 10% at 60 keV gave results identical to those for detectors that were not of spectrometry grade.

The other phenomenon observed was that of polarization induced at high dose-rates, (dose-rates polarization). However, since this was only observed for those detectors that exhibit bias induced polarization, it cannot be used to account for the non-linearity, although it may be related to the underlying phenomena.

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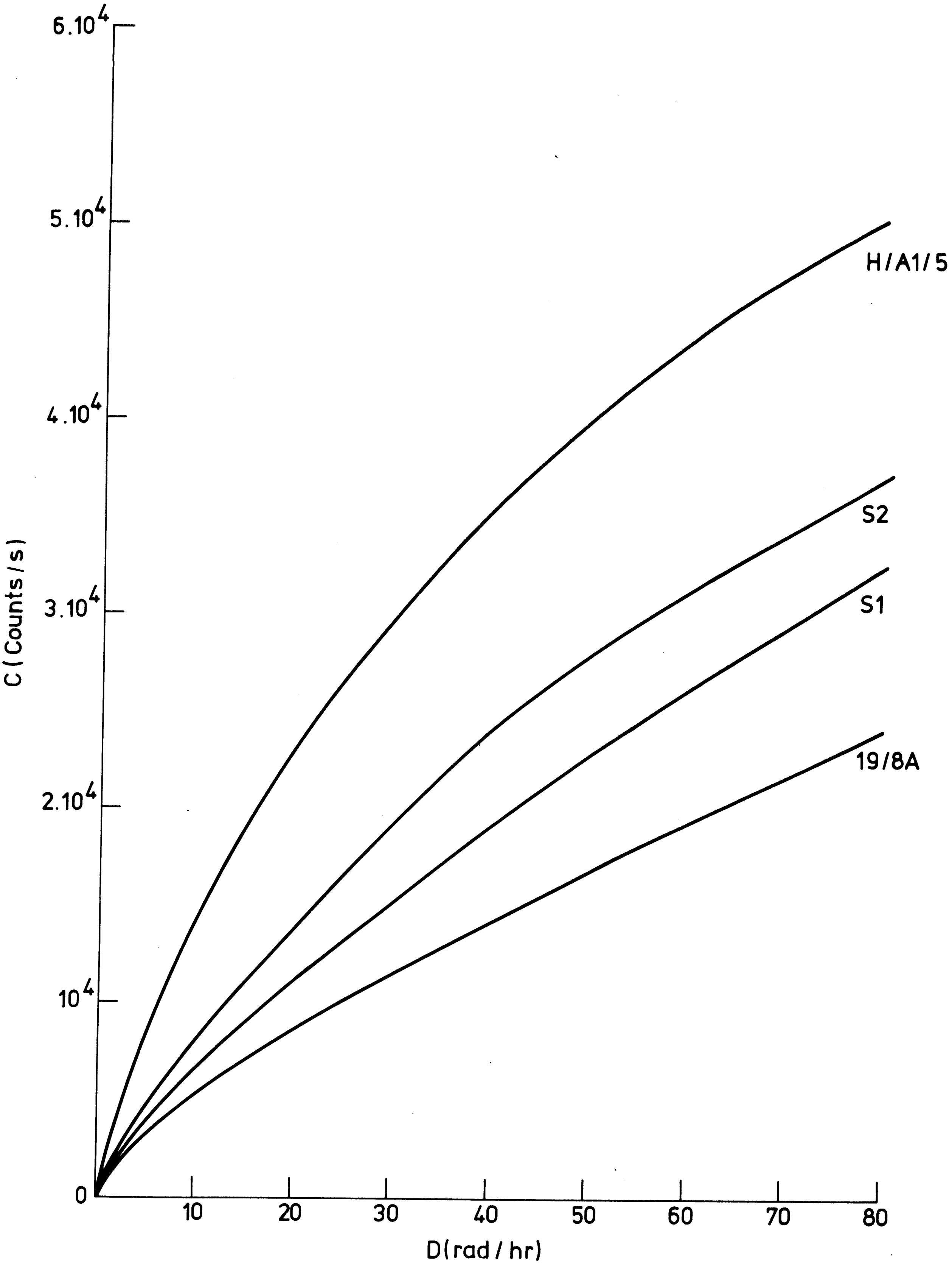
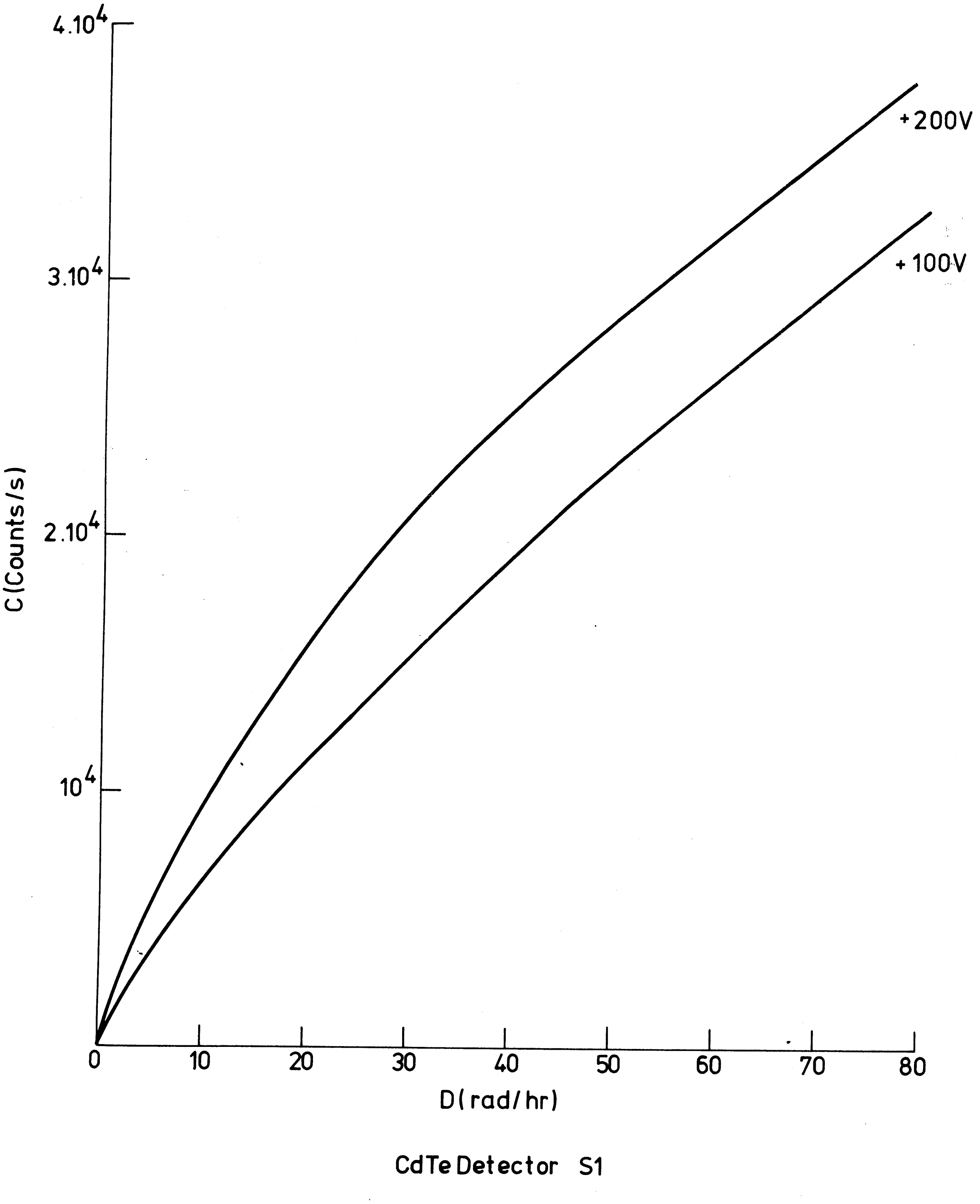
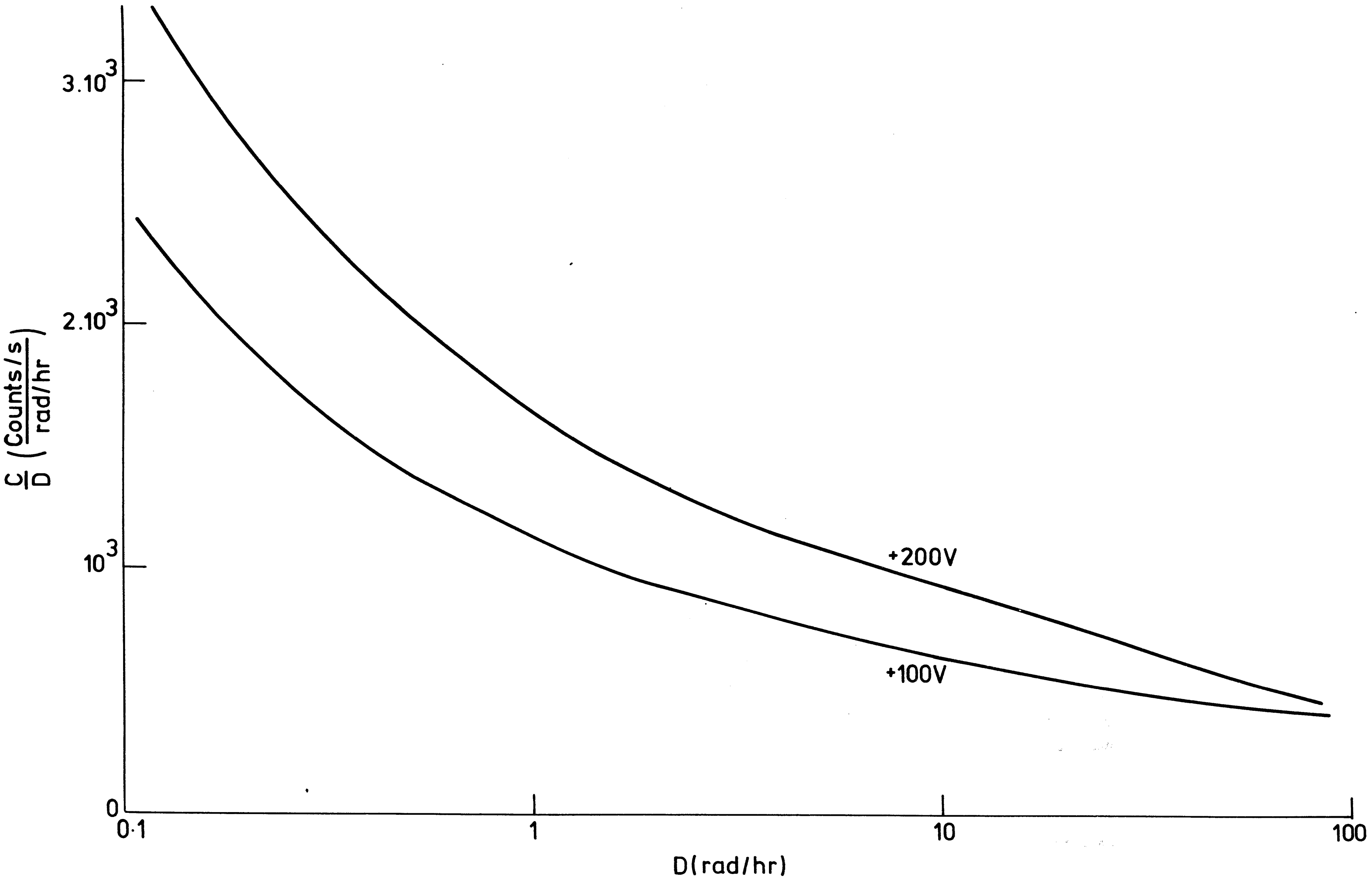


CdTe Detectors BIAS + 100V

AERE - R 9180 Fig. 1
Variation of count-rate (C) as a function of dose-rate (D) for several detectors using a fixed bias voltage of 100V.

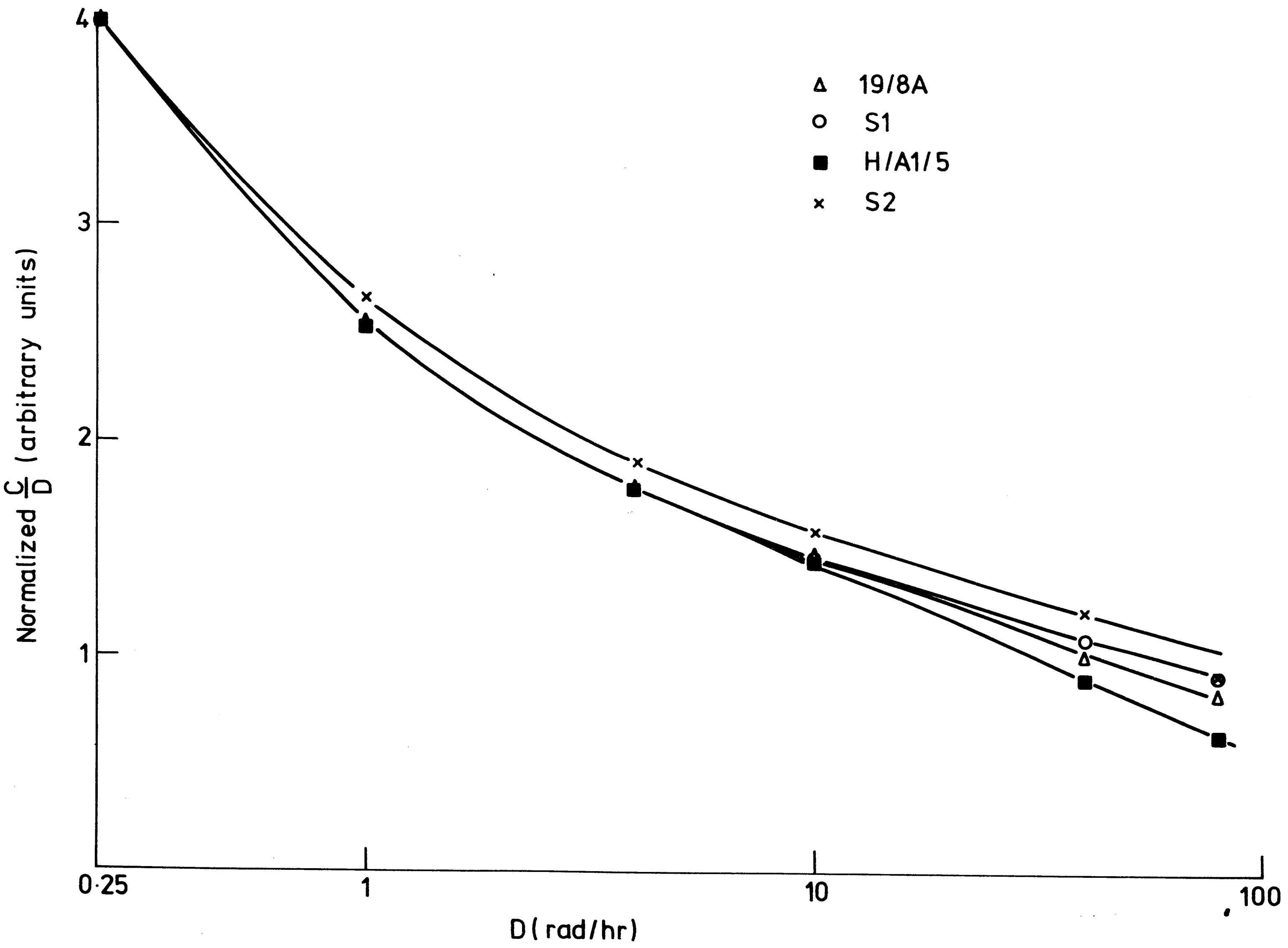


AERE - R 9180 Fig. 2
Variation of count-rate (C) as a function of dose-rate (D) for detector S1 at bias voltages of 200V and 100V.



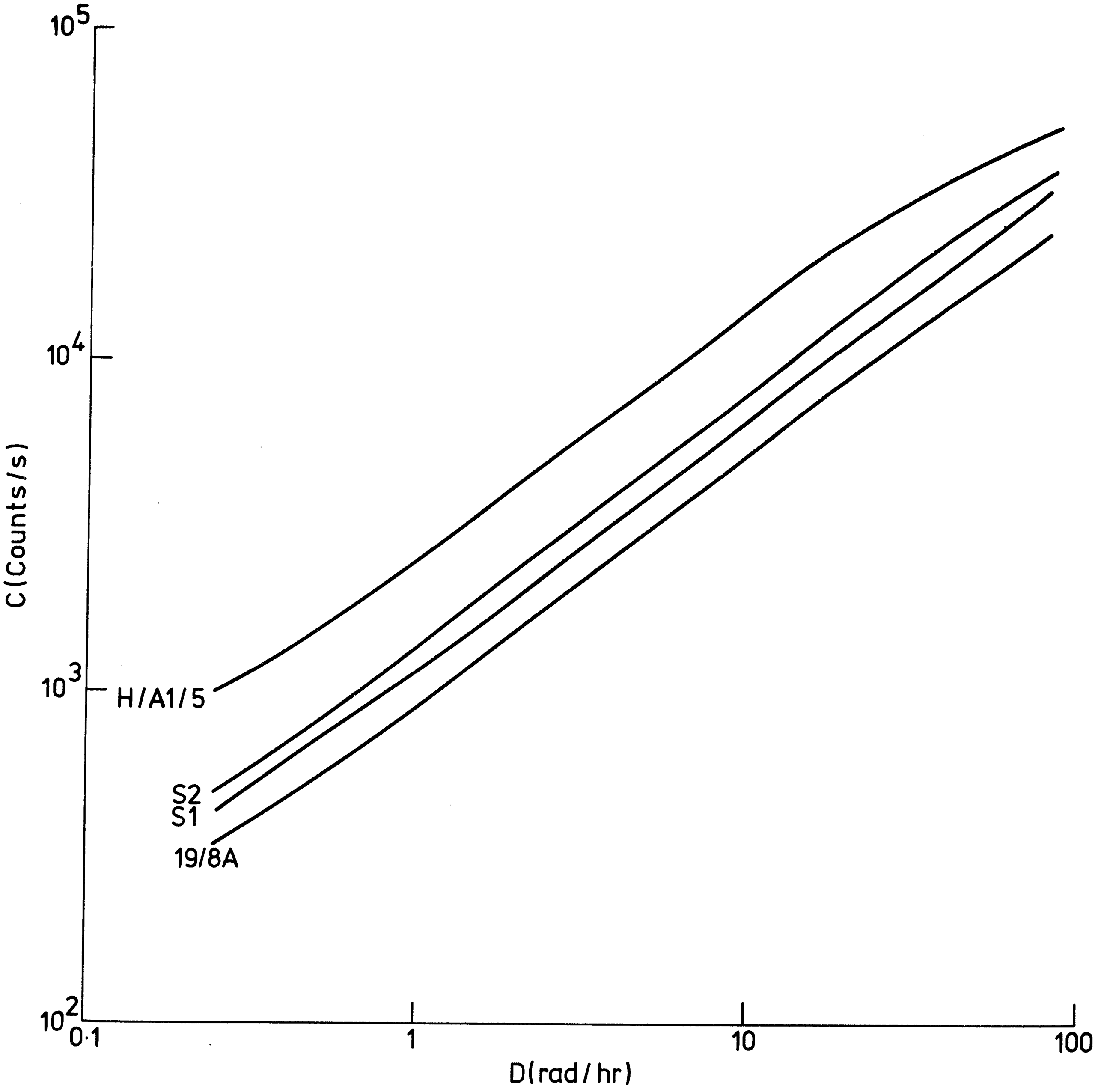
Cd Te Detector S1

AERE - R 9180 Fig. 3
Variation of the ratio C/D as a function of log D for detector S1 at bias voltages of 200V and 100V.



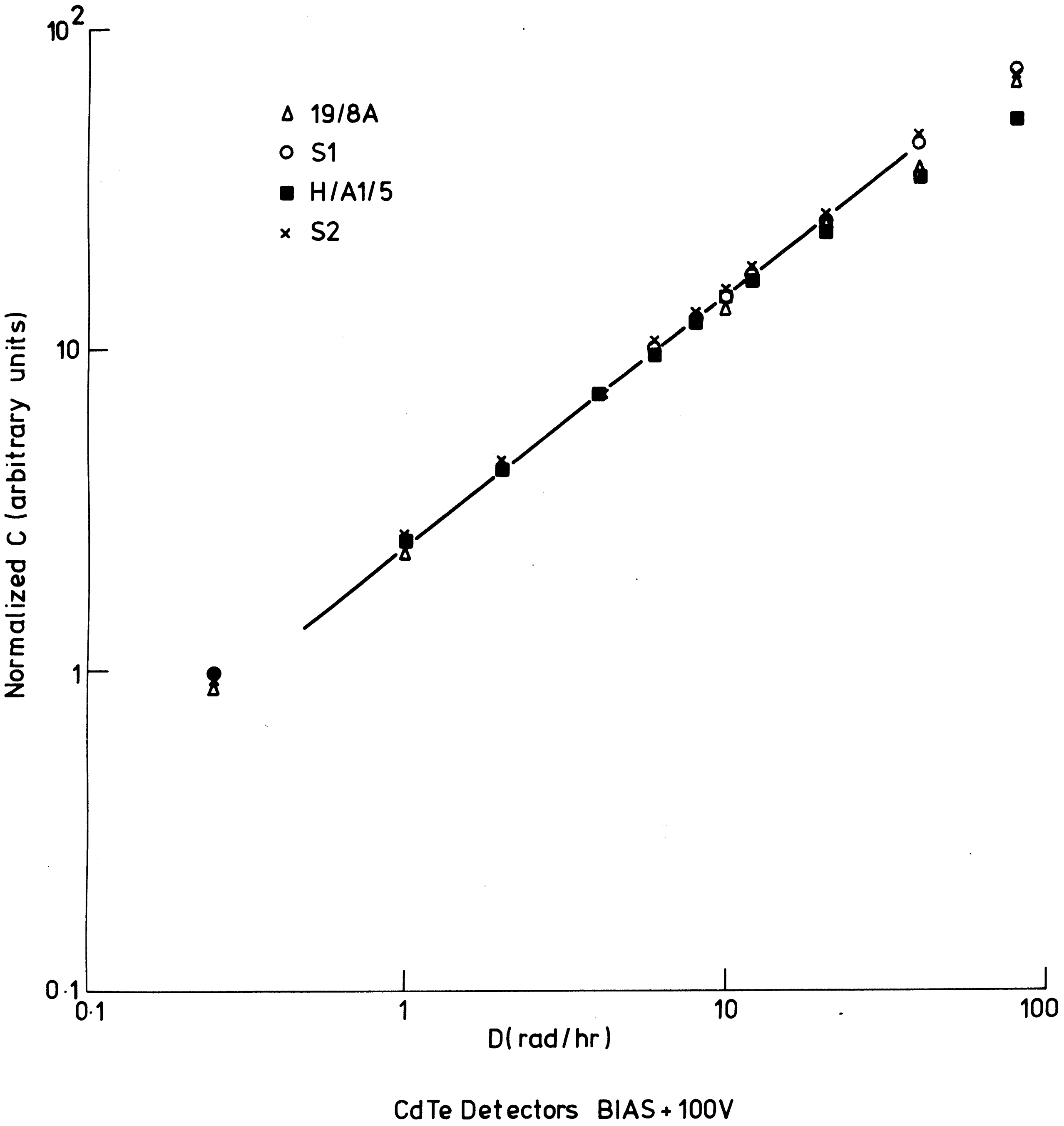
CdTe Detectors BIAS+100V

AERE - R 9180 Fig. 4
Variation of the ratio C/D (normalised) as a function of log D for several detectors at a fixed bias of 100V. C/D readings normalised to give the same value for all detectors at a dose-rate of 0.2 rad/hr.



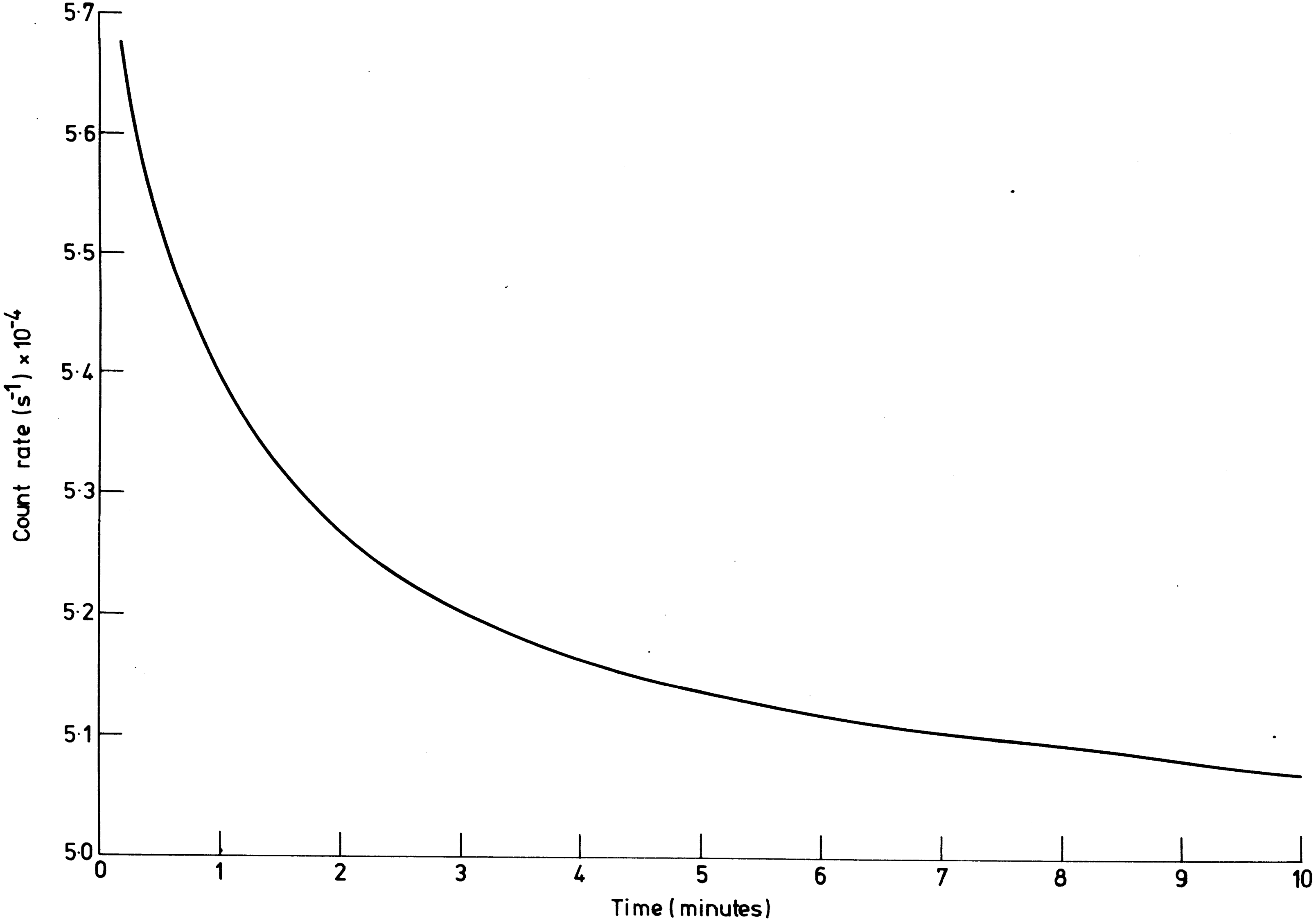
Cd Te Detectors BIAS+100V

AERE - R 9180 Fig. 5
Variation of log C as a function of log D for several detectors at a fixed bias of 100V.



AERE - R 9180 Fig. 6

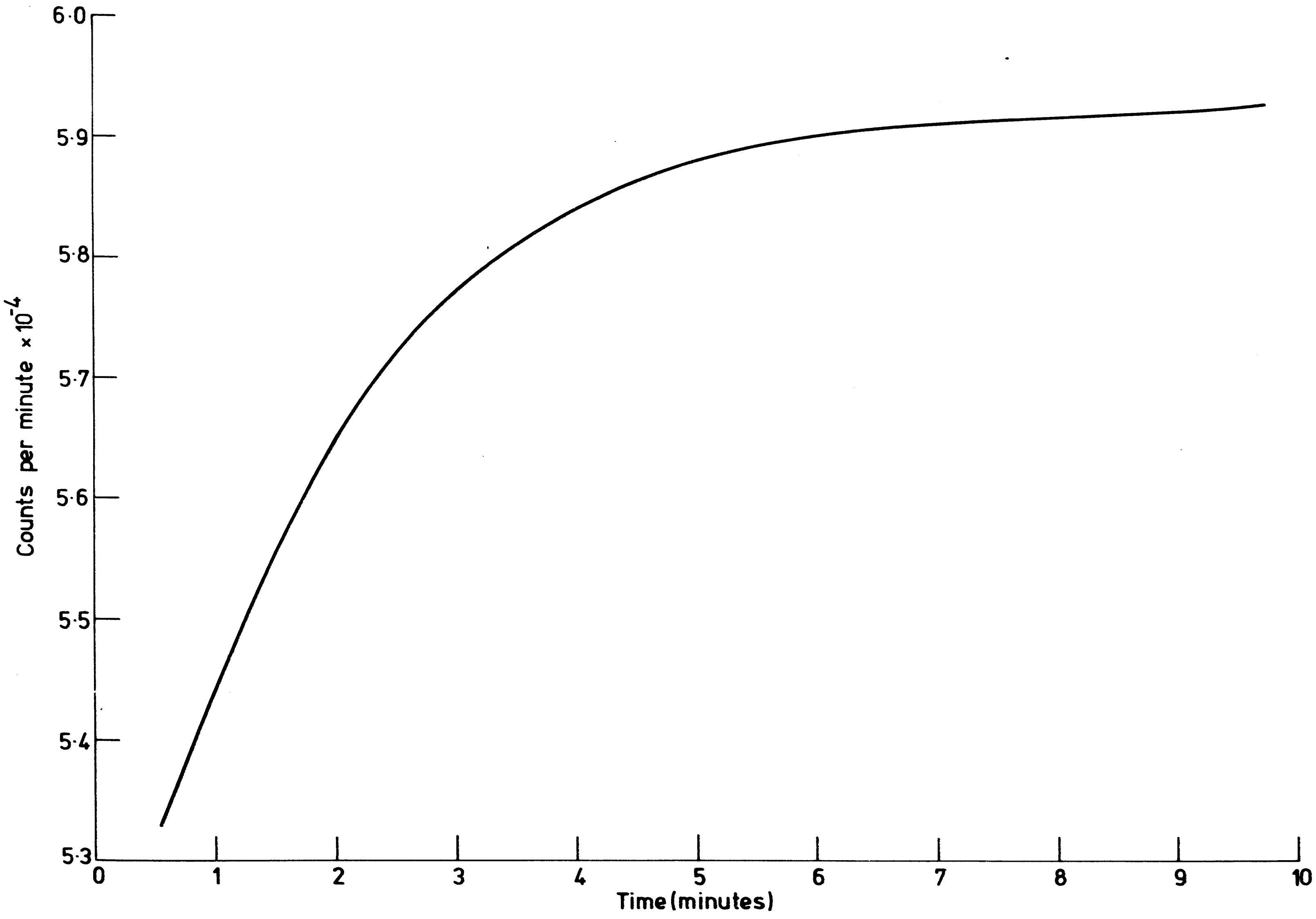
Variation of the log of the normalised count-rate (C) as a function of log D for several detectors at a fixed bias of 100V. Count-rates normalised to give the same value for all detectors at a dose-rate of 4 rad/hr.



CdTe Detector H/A1/5 BIAS 100V

AERE - R 9180 Fig. 7

Variation of count-rate (C) as a function of time of exposure to a dose-rate of 80 rad/hr.



CdTe Detector H/A1/5 BIAS 100V

AERE - R 9180 Fig. 8
Variation of count-rate (C) as a function of time of exposure to a dose-rate of 0.25 rad/hr, immediately following a 30 minute exposure to a dose-rate of 80 rad/hr.