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THE INTEGRATED SENSITIVITY OF HIGH-RANGE SOLID-STATE RADIACMETE--ETC(U)
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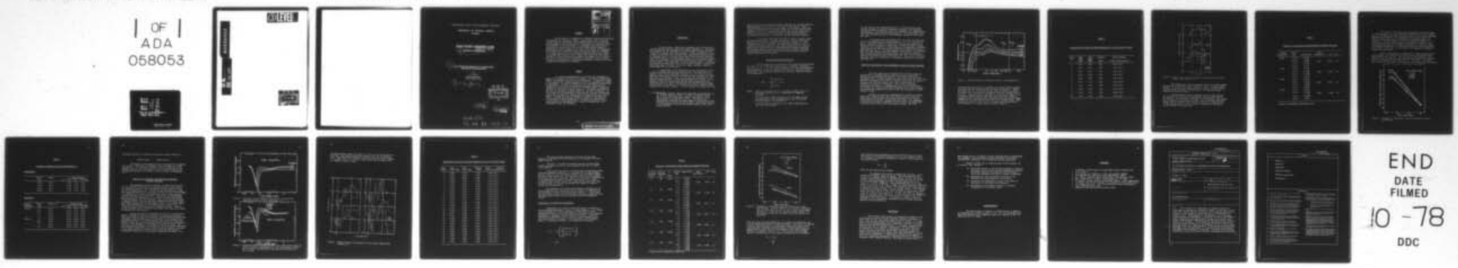

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(6) THE INTEGRATED SENSITIVITY OF HIGH-RANGE SOLID-STATE RADIACMETERS,

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ABSTRACT

The precision of a radiacmeter is commonly indicated by specifying its response as a function of energy. In this note, a more useful and relevant quantity is defined: the integrated sensitivity is a measure of the average or overall response of a radiacmeter to a radiation field. The dependence of the sensitivity of a high-range solid-state-detector radiacmeter on variations in fall-out and fission-product gamma-ray energy spectra and on changes in the lower cutoff energy is investigated. Both measured and calculated detector response functions are considered. It is found that the detector sensitivity remains constant with changes in the gamma spectra due to age to within about ±6% in the worst case considered. These results are encouraging, and suggest that the development of a small-scale solid-state-detector radiacmeter should continue. In addition, a procedure for calibrating radiacmeters is given, and future necessary investigations are proposed.

RÉSUMÉ

On caractérise généralement la précision d'un radiacmétre à partir de sa réponse en fonction de l'énergie. La présente communication définit une grandeur plus utile et plus pertinente: la sensibilité totale. C'est la mesure de la réponse moyenne ou globale du radiacmétre à un champ de rayonnement. On étudie la sensibilité d'un radiacmétre à l'état solide longue portée en fonction des variations du spectre énergétique des retombées et des produits de fission du rayonnement gamma, de même qu'en fonction de l'énergie de coupure inférieure. On prend en considération àla fois les fonctions de réponse mesurée et calculée du détecteur. On s'est apercu que la sensibilité du détecteur est constante à 6% près dans le pire des cas étudié, en fonction des variations du spectre de rayons gamma. Les résultats sont encourageants et permettent de croire que l'on est justifié de poursuivre la mise au point d'un radiacmétre à l'état solide de faible encombrement. On présente la marche à suivre pour étalonner les radiacmétres et on soumet un programme pour les recherches à venir qui s'imposent.

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INTRODUCTION

In recent years, a high range radiacmeter using a solid-state radiation detector has been developed at DREO by McGowan (1). The primary use envisaged for this instrument is the measurement of gamma-radiation fields due to fallout from nuclear weapons. In this application, it has a number of advantages over the high-range radiacmeters currently used by the Canadian Forces. The latter employ gas-filled ionization chambers. A solid-state detector is significantly smaller than an ionization chamber. Hence, the radiacmeter with a solid-state detector is inherently lighter and more compact, and is amenable to further miniaturization. In addition, it would have a longer shelf life, and it would be cheaper to produce for large-scale issue. Finally, it is a more rugged instrument, making it more suitable for use in the field.

A disadvantage of the solid-state-detector radiacmeter is that it does not measure the radiation dose directly. This means that the response factor relating the meter reading to the true dose rate at one gamma-ray energy may be different at another energy, and hence the instrument cannot be calibrated to give the true dose rate independent of the gamma-ray energy spectrum. It has been determined (1), however, that by placing a shield of an appropriate material and thickness around the solid-state detector, and by adjusting the depletion thickness and lower cutoff energy* of the device, it is possible to achieve a fairly uniform response as a function of energy. It is of interest to determine just how

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* The detector produces pulses whose amplitudes are proportional to the incident gamma-ray energy. In order to eliminate pulses due to noise, the pulses pass through a discriminator circuit before going to the count-rate circuit. The level of the discriminator determines the lowest gamma-ray energy that will be detected; this is called the cutoff energy. The response function of the radiacmeter at low photon energies depends on the cutoff energy selected.

sensitive is the total detector response, averaged over a fallout gamma-ray energy spectrum, to variations in the shape of the spectrum. These variations may result from, e.g., the nature of the surface on which the fallout is deposited and the different decay rates of the various fallout components. It is also important to know how the detector sensitivity varies with changes in the cutoff energy, so that the discriminator circuitry may be designed to achieve the required electronic stability.

It is evident that there is a need to define a quantity representing the mean detector response, weighted by a function which gives the relative importance of gamma rays of different energies. In this Technical Note, such a quantity is mathematically defined and will be called the integrated sensitivity (or simply sensitivity) of a detector. Sensitivities are calculated for measured detector response functions, with suitable gamma-ray spectra being taken from available literature. The dependences of detector sensitivity on spectral shape and cutoff energy are then noted and discussed.

DETECTOR INTEGRATED SENSITIVITY

All the pertinent data required for this study have been defined in terms of a set of gamma-ray energy groups or intervals, designated E_i, i = 1, 2, 3, ..., n. The number of groups, n, and the group boundaries are determined by the nature and quality of the data. This will become clear later. The integrated sensitivity may then be conveniently defined by the expression

$$S(t) = \frac{\sum_{i=1}^{n} \phi_i(t)\, D_i\, R_i}{\sum_{i=1}^{n} \phi_i(t)\, D_i},$$

Where $\phi_i(t)$ is the photon flux (as a function of fallout age t) in the energy interval E_i (i.e. ϕ represents the gamma-ray spectrum);

D_i is the tissue response function, i.e. the number of rads of tissue dose per unit incident photon flux, for photons having energies in the interval E_i;

R_i is the detector response in, e.g. rads/h (indicated) per unit dose rate (actual).

If $\phi_i(t)$ has the units (photons/cm^{2}sec) per (^{235}U fission/unit area), then the numerator in the above expression represents the radiacmeter reading per (^{235}U fission/unit area) due to photons of all energies while the denominator gives the tissue dose rate per (^{235}U fission/unit area). Thus, the resulting quotient is the radiacmeter reading per unit tissue dose rate.

It is obvious from the expression for S(t) that the ideal case would be a completely flat response function, i.e. R_i = a constant for all i. This would result in a sensitivity which is independent of the photon spectrum, and hence of fallout age. A number of tissue response functions, D_i, are available in the literature, corresponding to different definitions of the dose (e.g. first-collison dose, midline phantom dose, mean slab dose, etc.). For photon energies in the range to be considered here, all these functions are very similar. The particular function used in this study gives the maximum tissue-slab dose, as calculated by Claiborne and Trubey and given in Reference (2). Use of any of the other functions results in a difference in integrated sensitivity of not more than about 1%.

SENSITIVITY CALCULATIONS USING EXPERIMENTAL DETECTOR RESPONSE FUNCTIONS

The first sensitivity calculations were performed using the experimentally determined detector response functions reported by McGowan (1), and reproduced in Figure 1. The detector used for these measurements was a silicon photodiode having an area of 0.8 mm^2 and a total depletion thickness of about 130 μm. The four curves shown in Figure 1 represent four different values of the lower cutoff energy, E_c, determined by setting a discriminator level in the electronics associated with detector. A hemispherical brass filter approximately 1.9 mm thick was located between the detector and the source of photons. The response was normalized to unity for the ^{60}Co γ-rays with a cutoff energy of 58 keV.

Suitable γ-ray spectra, representative of fallout at various times after a fission blast, were taken from the work of French (3). These spectra were calculated for a point three feet above a smooth surface which is uniformly contaminated with fallout. The components of the total field due to scattering in the air and in the ground were calculated using a Monte Carlo-type computer program. The ^{235}U

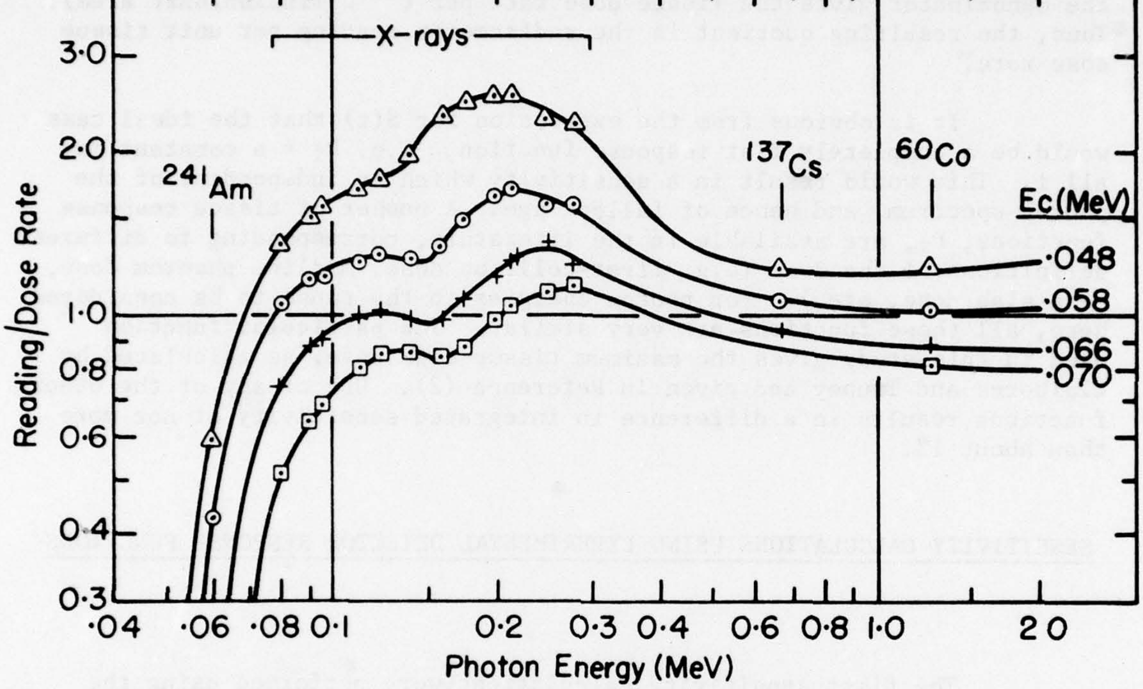

Figure 1. Measured radiacmeter response functions, from reference (1).

fission-product-decay spectra, excluding γ-rays from volatile products, were taken from the theoretical work of Nelms and Cooper (4). French considered only ten γ-ray energy groups; these are defined in Table 1. The spectra were calculated for 18 angular intervals, from near nadir to zenith. Since the angular dependence (in the vertical plane) of the radiacmeter response was not known, and since there was no obvious <u>a priori</u> reason for weighting the contributions from the various angles differently, the summed spectra were used for the present study. These spectra for times of 1.12 h, 23.8 h, 4.57 days, and 9.82 days after the detonation of a nuclear weapon are shown in Figure 2.

Table I

Energy-Interval Limits and Tissue Responses for the 10-Interval Scheme

Group No.	Lower limit (MeV)	Upper limit (MeV)	Midpoint (MeV)	Tissue Response (rads per (photon/cm^2))
1	0.04	0.06	0.05	8.72×10^{-11}
2	0.06	0.10	0.08	7.51×10^{-11}
3	0.10	0.18	0.14	1.25×10^{-10}
4	0.18	0.30	0.24	1.64×10^{-10}
5	0.30	0.50	0.40	2.76×10^{-10}
6	0.50	0.75	0.62	3.84×10^{-10}
7	0.75	1.00	0.88	4.82×10^{-10}
8	1.00	1.50	1.25	6.41×10^{-10}
9	1.50	2.50	2.00	8.86×10^{-10}
10	2.50	3.50	3.00	1.18×10^{-9}

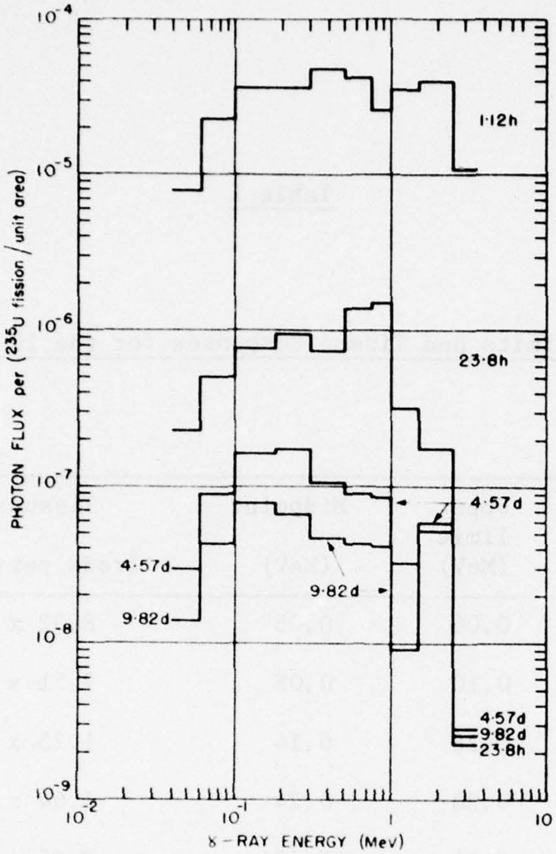

Figure 2. Fallout γ-ray spectra of various ages, summed over vertical angles, from Reference (3).

The energy groups used in reference (2) for the tissue response function are not the same as those defined by French. It was therefore necessary to calculate the tissue response for each of French's energy groups by using a weighted averaging scheme. The resulting tissue responses are given in Table 1.

The experimental detector response for each energy interval was determined by averaging the experimental curve over the width of the interval. When this was not possible (at low energies), the response at the midpoint of the interval was used. Note that because there are limited data for energies below 0.06 MeV, and none for energies above 1.5 MeV, energy groups 1, 9 and 10 did not contribute to the sums in the calculation of the sensitivity.

Table 2

Results of Calculations Using Experimental Response Functions

Cutoff energy (MeV)	Fallout Age	Sensitivity*	Mean Sensitivity*	S.D.*	%S.D.
0.048	1.12 hr	1.433	1.483	0.077	5.2
	23.8 hr	1.402			
	4.57 d	1.555			
	9.82 d	1.541			
0.058	1.12 hr	1.154	1.184	0.039	3.3
	23.8 hr	1.147			
	4.57 d	1.220			
	9.82 d	1.216			
0.066	1.12 h	0.974	0.985	0.018	1.8
	23.8 h	0.967			
	4.57 d	1.002			
	9.82 d	0.998			
0.070	1.12 h	0.875	0.879	0.008	0.9
	23.8 h	0.871			
	4.57 d	0.887			
	9.82 d	0.884			

* (Units of radiacmeter units/tissue rad.)

The results of the sensitivity calculations are shown in Table 2. For each value of E_c, the sensitivity averaged over the four fallout ages, the standard deviation of the sensitivity, and the relative standard deviation are presented. (The standard deviation is not used in the strictly correct sense here, but rather as a convenient measure of variation.) From the values of the relative standard deviation, it is evident that the sensitivity becomes less dependent on changes in the γ-ray spectrum as the cutoff energy is increased. Of course, E_c cannot be increased indefinitely, or a significant portion of the spectrum will not be taken into accout. For all values of E_c, however, the relative variation is less than 6%.

Figure 3 illustrates the dependence of detector sensitivity on cutoff energy. The relationship is nearly linear, and straight lines have been fitted to the data. The reduction of the dependence of the sensitivity on the spectral shape with increasing values of E_c, shows up here as a convergence of the lines near E_c = 0.07 MeV. In the first part of Table 3, the slopes of the lines are given, along with the relative

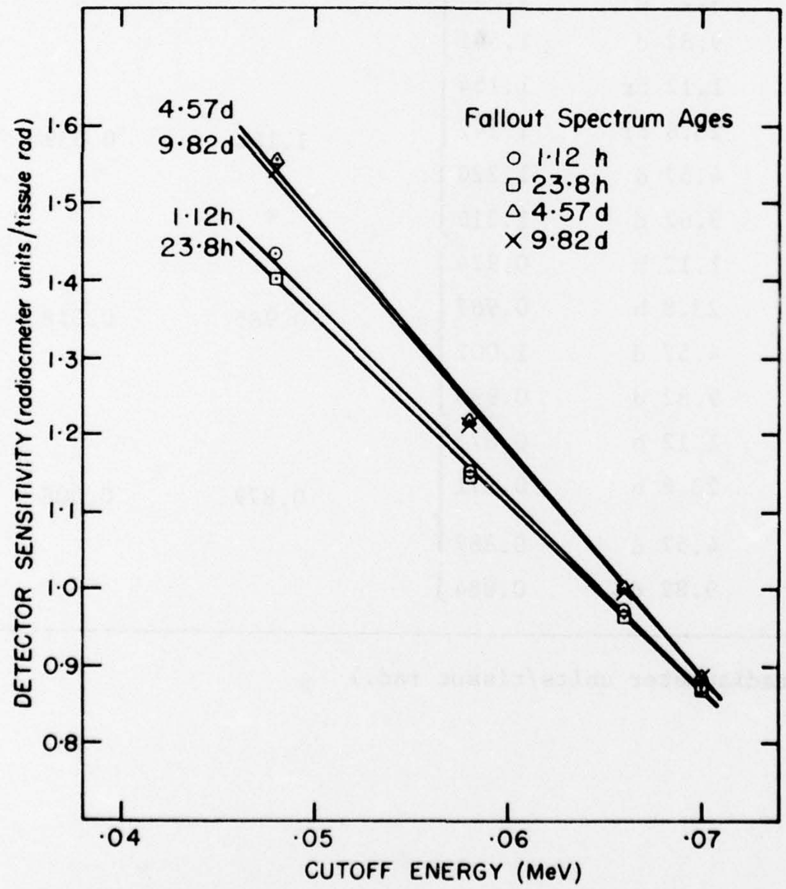

Figure 3. Dependence of experimental detector sensitivity on lower cutoff energy.

Table 3

Variation of Sensitivity with Cutoff Energy, E_c

Experimental

Fallout age	dS/dE_c	$(dS/S)/(dE_c/E_c)$ E_c = .05	.06	.07 MeV
1.12 h	-25.2	-0.92	-1.35	-2.03
23.8 h	-24.0	-0.89	-1.30	-1.93
4.57 d	-30.2	-1.02	-1.54	-2.40
9.82 d	-29.7	-1.01	-1.51	-2.36

Theoretical

Detector Thickness	Fallout age	$dS/dE_c \times 10^7$	$(dS/S)/(dE_c/E_c)$ E_c = .05	.06	.07 MeV
100 μm	1 h	-11.3	-0.53	-0.69	-0.94
	10 h	-11.3	-0.53	-0.70	-0.94
	1 d	-8.55	-0.44	-0.57	-0.74
	3 d	-8.95	-0.45	-0.59	-0.77
200 μm	1 h	-6.40	-0.22	-0.28	-0.34
	10 h	-6.40	-0.22	-0.28	-0.34
	1 d	-10.2	-0.33	-0.43	-0.54
	3 d	-8.45	-0.29	-0.37	-0.45

fractional variation of sensitivity with cutoff energy, defined by:

$$(dS/S)/(dE_c/E_c) = (dS/dE_c)/(E_c/S)$$

The meaning of this quantity is best illustrated by an example: if it equals - 0.92, then a 1% increase in E_c will result in a 0.92% decrease in S. It is evident from Table 3 that the magnitude of this quantity increases with increasing E_c; this is another reason for not increasing E_c too much in an effort to reduce the spectral dependence of S.

SENSITIVITY CALCULATIONS USING THEORETICAL DETECTOR RESPONSE FUNCTIONS

The experimental detector response functions which were used for the calculations reported in the preceding section do not exhibit very detailed structure. There are several possible reasons for this, but in the energy range 0.08 - 0.30 MeV the most important one is that the energy resolution of the X-ray source was not very good (30-50% FWHM). It is therefore of interest to determine the effect of better-defined response functions on the sensitivity. Theoretical calculations have been carried out by McGowan (5) for a variety of detector thicknesses, shield thicknesses, and cutoff energies. Some of the results are shown in Figures 4 and 5. Note the deep, well defined minima in these curves which were not evident in the experimental curves. In an actual radiacmeter, these minima would not be so sharp because of noise in the electronics and electron scattering by extraneous material. Thus the curves in Figures 4 and 5 represent more extreme cases than one is likely to encounter in a real detector.

In order to properly investigate the effect of a well-resolved detector response function, more detailed γ-ray spectra than those of French are required. Fallout calculations or measurements satisfying this requirement could not be found in the literature, so the results of an experimental study of ^{235}U fission-product γ-ray spectra (6) were used instead. These data may not represent fallout spectra very realistically, but this is not important for the purpose of the present study. The main concern here is simply to ascertain the effect of spectral variations on the detector sensitivity, not to model an actual situation. The ages of the fission products in reference (6) are not the same as those considered by French (3), but the range of magnitudes is similar. For

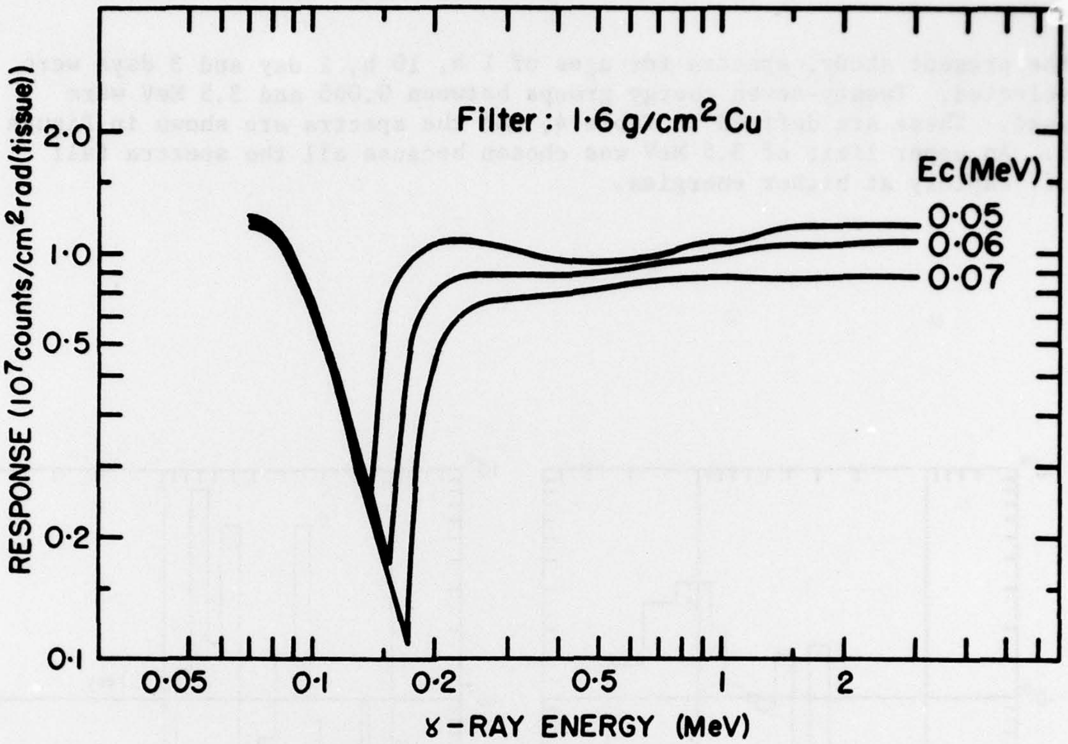

Figure 4. Calculated detector response functions for a 100-μm-thick depletion region in silicon, from McGowan (5).

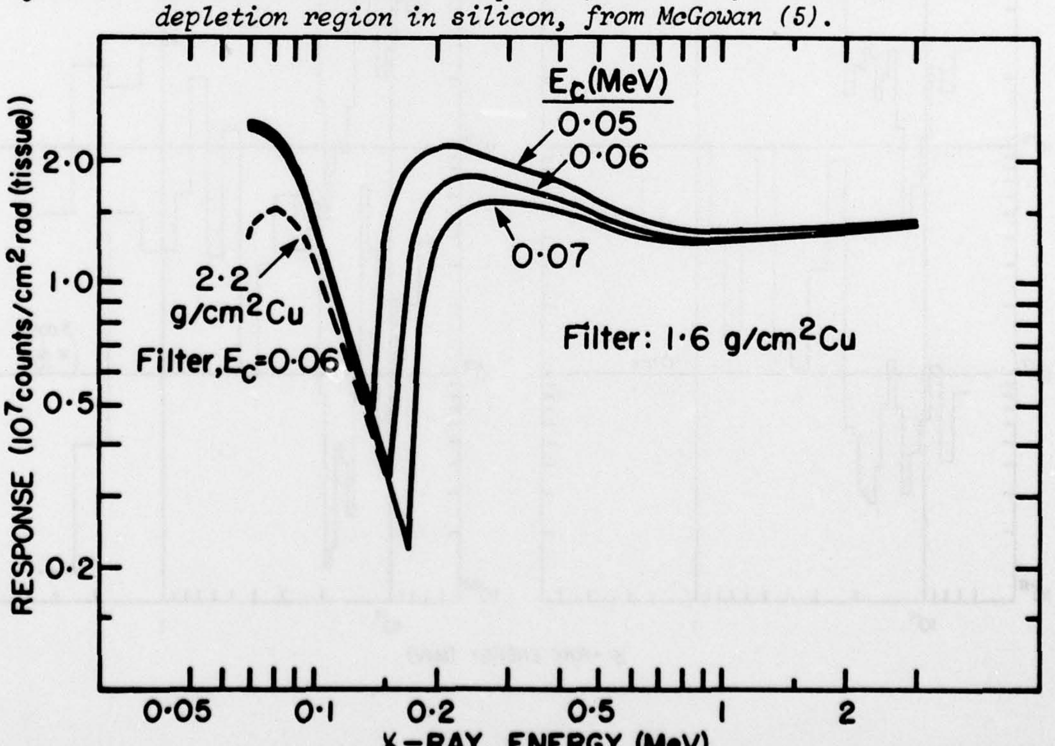

Figure 5. Calculated detector response functions for a 200-μm-thick depletion region in silicon, from McGowan (5). For γ-ray energies greater than 0.150 MeV, the dashed curve overlies the solid curve for E_C = 0.06 MeV.

the present study, spectra for ages of 1 h, 10 h, 1 day and 3 days were selected. Twenty-seven energy groups between 0.065 and 3.5 MeV were used. These are defined in Table 4, and the spectra are shown in Figure 6. An upper limit of 3.5 MeV was chosen because all the spectra fall off rapidly at higher energies.

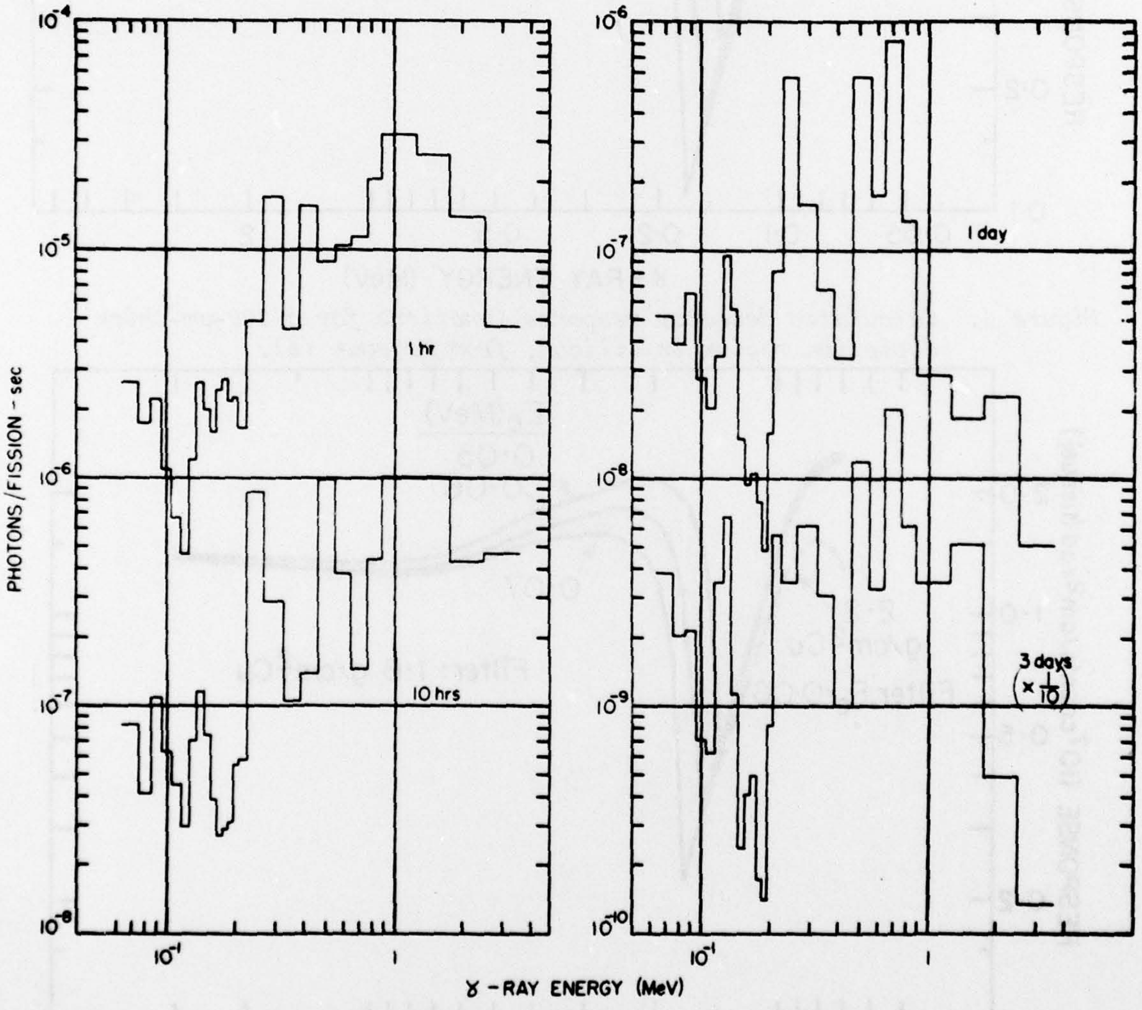

Figure 6. Fission fragment γ-ray spectra of various ages, adapted from reference (6).

Table 4

Energy-Interval Limits and Tissue Responses for the 27-Interval Scheme

Group Number	Lower limit (MeV)	Upper Limit (MeV)	Midpoint (MeV)	Tissue Response (rads per (photon/cm^2))
1	0.065	0.075	0.070	7.85×10^{-11}
2	0.075	0.085	0.080	7.44×10^{-11}
3	0.085	0.095	0.090	7.44×10^{-11}
4	0.095	0.105	0.100	8.77×10^{-11}
5	0.105	0.115	0.110	1.01×10^{-10}
6	0.115	0.125	0.120	1.01×10^{-10}
7	0.125	0.135	0.130	1.01×10^{-10}
8	0.135	0.145	0.140	1.01×10^{-10}
9	0.145	0.155	0.150	1.32×10^{-10}
10	0.155	0.165	0.160	1.64×10^{-10}
11	0.165	0.175	0.170	1.64×10^{-10}
12	0.175	0.185	0.180	1.64×10^{-10}
13	0.185	0.195	0.190	1.64×10^{-10}
14	0.195	0.205	0.200	1.64×10^{-10}
15	0.205	0.225	0.215	1.64×10^{-10}
16	0.225	0.265	0.245	1.64×10^{-10}
17	0.265	0.325	0.295	1.99×10^{-10}
18	0.325	0.385	0.355	2.48×10^{-10}
19	0.385	0.465	0.425	2.69×10^{-10}
20	0.465	0.555	0.510	3.60×10^{-10}
21	0.555	0.645	0.600	3.60×10^{-10}
22	0.645	0.765	0.705	4.26×10^{-10}
23	0.765	0.885	0.825	4.82×10^{-10}
24	0.885	1.245	1.065	5.90×10^{-10}
25	1.245	1.745	1.495	7.25×10^{-10}
26	1.745	2.495	2.120	9.09×10^{-10}
27	2.495	3.545	3.020	1.18×10^{-9}

The tissue response function of reference (2) was again modified, in the manner described previously, to correspond to the new energy intervals.

The value of the detector response function for each energy interval was taken to be that of the calculated point near the center of the interval.

Table 5 gives the results of the sensitivity calculations using theoretical response functions. It is evident that the sharp minimum does not result in a very significant change in the fractional standard deviation of the sensitivity. The values are still low, not exceeding 5% in any of the cases calculated. Again it is found that the sensitivity is less dependent on spectral shape for large values of E_c. These calculations also indicate that a 200 μm detector performs better than one 100 μm thick, but further calculations are required in order to optimize all the parameters.

The dependence of the theoretical detector sensitivity on the cutoff energy was also investigated, and the results are summarized in the second part of Table 3 and are plotted in Figure 7. It was found that the relative fractional variation again increases in magnitude with increasing cutoff energy; this is consistent with the experimental results.

Calibration of a Solid-State Radiacmeter

Radiacmeters are normally calibrated against a radioactive source emitting monoenergetic γ-rays of a known intensity. It is evident that the response of a solid-state-detector radiacmeter to these monoenergetic photons will not necessarily be the same as its integrated sensitivity to the gamma radiation produced by fallout. A means of calibrating a radiacmeter in such a way as to give a measure of the dose due to fallout is required. This may be done in the following manner. A calibration constant, k, is defined by the equation:

$$S_f = k \left(\frac{\sum_{i=1}^{n} \phi_i(t)\, D_i\, R_i}{\sum_{i=1}^{n} \phi_i(t)\, D_i} \right)$$

$$= kS,$$

Table 5

Results of Calculations Using Theoretical Response Functions

Cu filter thickness (g/cm^2)	Detector thickness (μm)	E_c (MeV)	Fallout age	Sensitivity*	Mean Sensitivity*	S.D.*	%S.D.
1.6	100	0.050	1 h	1.068	1.026	0.047	4.6
			10 h	1.064			
			1 d	0.980			
			3 d	0.991			
1.6	100	0.060	1 h	0.977	0.943	0.037	3.9
			10 h	0.972			
			1 d	0.907			
			3 d	0.917			
1.6	100	0.070	1 h	0.841	0.825	0.017	2.1
			10 h	0.839			
			1 d	0.809			
			3 d	0.812			
1.6	200	0.050	1 h	1.440	1.473	0.042	2.8
			10 h	1.445			
			1 d	1.531			
			3 d	1.475			
1.6	200	0.060	1 h	1.372	1.389	0.023	1.7
			10 h	1.378			
			1 d	1.423			
			3 d	1.383			
1.6	200	0.070	1 h	1.312	1.316	0.009	0.7
			10 h	1.317			
			1 d	1.328			
			3 d	1.306			
2.2	200	0.060	1 h	1.316	1.322	0.018	1.3
			10 h	1.320			
			1 d	1.346			
			3 d	1.304			

* Units of 10^7 counts/(cm^2. tissue rad)

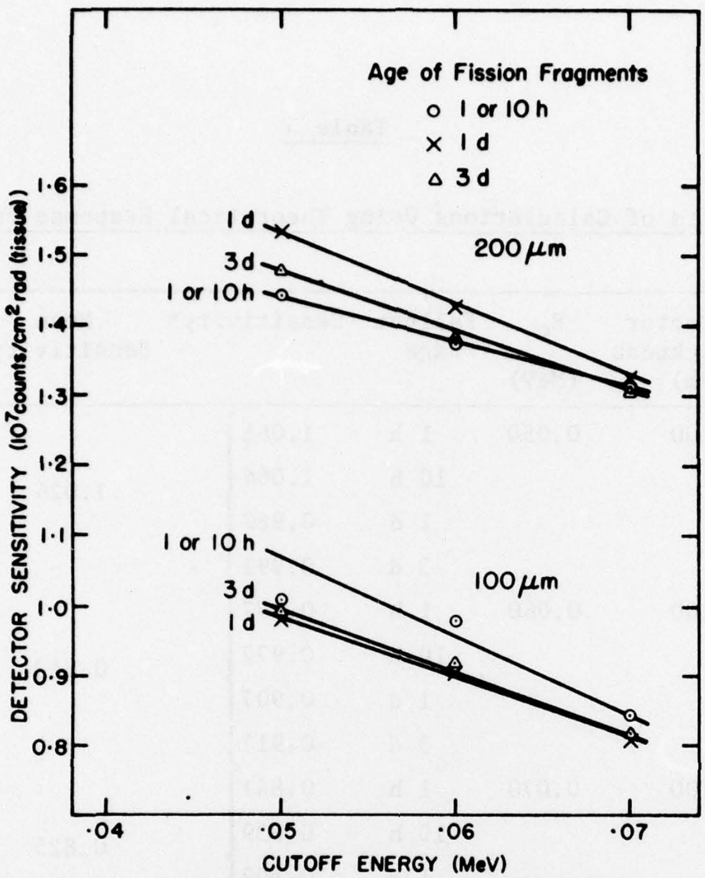

Figure 7. Dependence of theoretical detector sensitivity on lower cutoff energy. The poor linear fits for the 100- μm detector data are due to the fact that for the 0.07-MeV cutoff energy, the amount of energy lost by a photon normally incident on the detector is less than 0.07-MeV, and so the pulse is not registered.

where S_f is the calibrated sensitivity to a fallout γ-ray spectrum, and S is the uncalibrated quantity defined previously. The factor k is required to have a value such that S_f = 1 (indicated rad/h)/(true rad/h), where "true rad" may be defined in whatever sense is deemed appropriate, e.g. midline phantom tissue dose, and is determined by the tissue response function, D_i, adopted. Hence, $k = S^{-1}$. For a γ-ray source emitting photons in energy group j, the integrated sensitivity, S_s, is simply:

$$S_s = k R_j$$

$$= \frac{R_j}{S}$$

Thus calibrating the radiacmeter to give a sensitivity S_s to a source will result in the desired calibration of $S_f = 1$ for a fallout field. If one wishes to consider an average over a range of fallout ages, the expression becomes:

$$\bar{S}_s = \frac{\bar{R}_j}{\bar{S}}$$

where the bars indicate age averages.

Two examples will be given to clarify this procedure. First, consider a calibration using the isotope ^{137}Cs which emits 0.66 MeV γ-rays and is commonly used as a standard source. For the theoretical detector response function for a 100-μm-thick detector with a 1.6-g/cm^2 Cu filter and cutoff energy of 60 keV, the mean sensitivity, $\bar{S}$, is 0.943 x 10^7 cm^{-2}rad^{-1} (Table 5). The corresponding value of R_j (from Figure 4) is 0.93 x 10^7 cm^{-2}rad^{-1} . Hence, the required detector sensitivity to the source is $\bar{S}_s = 0.99$. Second, ^{60}Co sources are also often used for calibration purposes, and emit 1.17- and 1.33-MeV γ-rays. If the detector is now taken to be 200 μm thick, with a 1.6-g/cm^2 Cu filter and a cutoff energy of 50 keV, then $\bar{S} = 1.473 \times 10^7$ cm^{-2}rad^{-1} (from Table 5) and R_j = 1.35 x 10^7 cm^{-2}rad^{-1} (from Figure 5). In this case, then, the radiacmeter would be calibrated with a ^{60}Co source to give a reading of $\bar{S}_s = 0.92$ (indicated rad/h)/(true rad/h). In practice, of course, it would be desirable to use experimentally determined detector response functions, measured with good resolution.

CONCLUSIONS

The military specifications for radiacmeters designed for use in the field (7) require that the instrument response be constant to within ±20% over the γ-ray energy range of 0.08 to 3.0 MeV. It is felt that a more practical measure of the uniformity of response of a radiacmeter is the integrated sensitivity as defined in this note, since this quantity gives the relationship between the instrument reading and the radiation dose due to a typical γ-ray spectrum. If this sensitivity is accepted as a valid measure of radiacmeter consistency, then the results reported in this note indicate that significant changes in a fallout γ-ray spectrum do not greatly affect the reliability of a solid-state-detector radiacmeter. A conservative estimate of the possible error in a radiacmeter reading due to spectral variation is ±10% for any reasonable tissue response functions which might be chosen, which is small enough that it is unlikely to be the limiting factor in determining the instrument. This conclusion confirms the utility of the solid-state-detector radiacmeter for the projected military application.

However, further work is required before a final proposal can be drafted. This includes:

(a) theoretical studies to find optimum thicknesses of detector and filter, and to account for the differences in relative fractional variations in sensitivity with E_C between theory and experiment (this work is already in progress);

(b) experiments to test and confirm the results of (a), preferably with high-resolution γ-ray sources;

(c) theoretical and experimental studies of the effect of non-normal γ-ray incidence on the detector;

(d) determination of the angular response of prototype radiacmeters in the vertical plane;

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(U) The precision of a radiacmeter is commonly indicated by specifying its response as a function of energy. In this note, a more useful and relevant quantity is defined: the integrated sensitivity is a measure of the average or overall response of a radiacmeter to a radiation field. The dependence of the sensitivity of a high-range solid-state-detector radiacmeter on variations in fall-out and fission-product gamma-ray energy spectra and on changes in the lower cutoff energy is investigated. Both measured and calculated detector response functions are considered. It is found that the detector sensitivity remains constant with changes in the gamma spectra due to age to within about ±6% in the worst case considered. These results are encouraging, and suggest that the development of a small-scale solid-state-detector radiacmeter should continue. In addition, a procedure for calibrating radiacmeters is given, and future necessary investigations are proposed.

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