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A SPECTRAL STRIPPING METHOD FOR A GE SPECTROMETER
USED FOR INDOOR GAMMA EXPOSURE RATE MEASUREMENTS

By
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July 1984

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ABSTRACT

A gamma ray spectrum stripping method has been adapted to a Ge spectrometer for in situ measurements of exposure rates in air. This method involves subtracting out from a collected spectrum those counts that represent cosmic-ray events or partial absorption of gamma rays in the detector. The resultant total absorption spectrum is converted to flux incident at the detector, which is then used to compute exposure in air. The appropriate stripping and flux conversion parameters were determined by calibrating the detector for both full absorption peak and partial absorption continuum efficiency for parallel incident flux. This technique has particular application in indoor radiation measurements, where separate estimates of the gamma and cosmic ray exposure rates are desired and can also be used for deriving the energy distribution of a gamma-radiation field.

INTRODUCTION

In situ techniques for assessing the penetrating components (gamma plus cosmic-ray secondaries) of a radiation field have been used successfully in the outdoor environment (Gogolak, 1982; Beck et al., 1972a). An ionization chamber is used to provide a measurement of the total exposure rate without knowing the exact spectral composition of the gamma field or the relative contributions of the gamma and cosmic radiation (DeCampo et al., 1972). A gamma-ray spectrometer, via the analysis of full absorption peaks, is used to measure the uncollided flux from the various radionuclides in the soil. The open field source geometry is fairly well modeled by assuming an infinite half-space having a uniform profile with depth for natural emitters, and an exponentially decreasing profile with depth for fallout emitters. The resulting measured fluxes can be converted to concentrations or inventories in the soil and also to exposure rates in the air above (Beck et al., 1972b).

In principle, the same methods can be applied to indoor radiation measurements. However, the source distribution can be far more complex and is generally unknown. For this situation, it is desirable to have an independent method of determining the gamma exposure rate that does not require any assumptions of the source geometry. Our method, described herein, provides such a means. Spectrum stripping is used to give a measure of the total flux (scattered as well as uncollided flux), which can be converted to gamma exposure rate. This value can be subtracted from the total exposure rate reading of an ionization chamber to give the cosmic ray exposure rate (Miller and Beck, 1983). (In a strict sense, the quantity 'exposure rate' is only applied to gamma rays of certain energies, however, for our purposes we extend the meaning to include the exposure rate equivalent of ionization due to cosmic rays.)

INSTRUMENTATION AND THEORY

Conversion of a NaI gamma-ray spectrum to exposure rate has been performed by several investigators using various techniques (Okano et al., 1980; Minato and Kawano, 1970; Moriuchi and Miyanaga, 1966). The method of Moriuchi and Miyanaga (1966) has been adapted to a Ge(Li) spectrometer (Terada et al., 1980). Here, we apply the method of Okano et al. (1980) with some modifications, to an intrinsic Ge detector. This detector is a closed ended coaxial cylinder 59 mm in diameter and 35 mm in length, with an efficiency for a point source at 25 cm of 22.3% at 1.33 MeV relative to a 7.5 x 7.5 cm NaI(Tl) crystal. It is mounted in a small (1.8 L) liquid nitrogen cryostat that features an all-attitude capability. The spectrum is collected in a portable multichannel analyzer that also provides high voltage and pre-amp power to the detector.

A count registered by the detector can be caused by the full or partial absorption of an incident photon or by the passage of a cosmic ray produced

charged particle. In order to convert to a gamma-exposure rate, the spectrum must be stripped of the partial absorption and cosmic-ray events leaving only the events corresponding to the full absorption of a gamma ray. The resulting spectrum, which represents both primary as well as scattered photons, can then be converted to the total incident flux spectrum by applying the full absorption efficiency curve of the detector. The flux spectrum is then used to convert directly to exposure rate in air.

COSMIC-RAY EVENTS

The cosmic ray count rate in the region below 3 MeV in a typical Ge detector is generally small compared to the gamma count rate. Since there is no natural gamma line present between 3 and 4 MeV, this region is used to estimate the cosmic ray count rate which is then extrapolated back to 0 MeV and subtracted out from the spectrum. Although there may be some variation in the energy distribution, we have assumed that the cosmic continuum is flat in this region. While there is undoubtedly some buildup at low energies in an outdoor environmental spectrum or one from within a light frame house, this effect can be neglected because most of the counts in this region would come from scattered terrestrial gamma radiation. When a spectrum is taken in a massive building, the buildup effect becomes even less important due to the filtering out of the soft component of cosmic radiation.

PARTIAL ABSORPTION EVENTS

The events corresponding to partial absorption in the detector make up a large fraction of the counts in the spectrum and are not as simple to strip out. For the most part, these events are the result of Compton scatter in the crystal itself or the surrounding cryostat. For single scatter events, a continuum of counts will form in the spectrum reaching a maximum energy at the Compton edge given by

$$E_c = E_p - \left(\frac{2}{0.511} + \frac{1}{E_p} \right)^{-1} \quad (1)$$

where

E_c is the energy of the Compton edge (MeV), and
 E_p is the energy of the incident gamma ray (MeV).

Okano et al. (1980) have used a distribution of counts with energy which is essentially a single step function between the low end of the spectrum and

E_c . An example of the actual distribution in our detector is shown in Figure 1. Aside from the non-linearity below E_c , it can be seen that there are a number of counts that lie above E_c , which are a result of multiple scatter events within the crystal. Based on this, a multiple step function fit to the continuum was incorporated into the stripping routine. The region below E_c is divided into 10 equal size energy bands and the region between E_c and E_p is divided into 4 equal size bands. The assumed fractional continuum counts for each band are compared to the measured distribution as shown in Figure 1. Although the shape of the continuum is actually a function of the energy and incident angle of the gamma ray, we have found that, for our detector, it is not overly sensitive to these variables, particularly at the higher energies which contribute the most to the exposure rate. It should be noted that the peak which occurs at $E_p - E_c$ (0.185 MeV) in Figure 1 is a result of the total absorption of gamma rays backscattered from the coldfinger behind the crystal. It is not accounted for in the continuum fit because it is only present at angles near normal incidence to the detector face, and is only associated with a small fraction of the total 4π solid angle.

STRIPPING OPERATION

Using the assumed shapes for the cosmic and partial absorption continua, the following computerized stripping operation is applied to the spectrum across equal size energy bands.

$$N'_i = N_i - \sum_{j=i+1}^L f_{ij}(r_j - 1)N'_j - N_c \quad (2)$$

where

- N'_i, N'_j = the counts in an energy band due to the total absorption of incident gamma flux,
- N_i = the observed counts in an energy band due to all sources,
- L = the energy band containing the highest energy gamma line (2.615 MeV),
- f_{ij} = the fraction of the continuum counts at energy band i due to the partial absorption of incident gamma flux at energy band j ,
- r_j = the ratio of total counts to full absorption peak counts for incident flux at energy band j , and
- N_c = the counts due to cosmic-ray events, assumed to be constant in any energy band i and given by

$$N_c = (E_2 - E_1 + 1)^{-1} \sum_{i=E_1}^{E_2} N_i \quad (3)$$

where

E_1 and E_2 = the lower and upper energy bands of a pure cosmic ray energy interval (3 - 4 MeV).

Although a spectrum is generally collected at 1 keV per channel for optimum resolution of peaks, energy bands 10 keV in width are used in the stripping operation to reduce the number of computations. This substantially reduces the running time of the computer program without significantly affecting the accuracy of the results. The stripping operation is initiated at the energy band containing the highest energy gamma line (2.615 MeV), where $N' = N - N_c$ and the operation continues for succeeding lower energy bands. It is necessary to proceed in this order since N'_j is needed to compute any lower N'_i . The entire stripping operation takes 3 minutes to run on a Hewlett-Packard 9825B desktop computer using HPL programming language.

The quantity r is computed from

$$r(E) = \frac{\epsilon_t(E)}{\epsilon_p(E)} \quad (4)$$

where

ϵ_p = the full absorption peak efficiency for parallel incident flux at energy E (cpm/ γ /cm²-s), and
 ϵ_t = the total (peak plus continuum) efficiency for parallel incident flux at energy E (cpm/ γ /cm²-s).

These efficiencies were obtained by performing a shadow shield experiment on the detector. A monoenergetic point source was placed several meters from the detector and a spectrum was taken. A shield sufficient to stop essentially all primary gamma rays from the source was then interposed so as to geometrically shadow the detector from the source, and a spectrum was taken and subtracted from the original. In this manner, scattered radiation from

the room's walls, floor and ceiling, as well as any background radiation, is cancelled out, leaving a spectrum that represents the direct parallel flux from the source. This flux is simply given by

$$\phi = \frac{Se^{-\mu d}}{4\pi d^2} \quad (5)$$

where

- ϕ = the primary flux incident on the detector ($\gamma/\text{cm}^2\text{-s}$),
- S = the source strength (γ/s),
- d = the distance between source and detector (cm)
- μ = the air attenuation coefficient for the source gamma energy (cm^{-1}).

The observed full absorption peak count rate and total count rate, each divided by the flux, gives ϵ_p and ϵ_t , respectively. This experiment was performed at various energies in order to obtain a smooth curve for r versus E . The results are shown in Figure 2.

One complication is that a cylindrical Ge detector such as this does not have a uniform response over all angles of incidence. Although the continuum shape as a function of angle is not a critical factor, the angular response of the quantity r must be taken into account. Figure 3 shows an example of the angular dependence of r at one particular energy. This angular dependence is not a strong function of energy, so one can apply a single correction factor representative of the higher energies which weigh heavily in the final exposure rate computation. For an isotropic radiation field, the average response over the entire solid angle is given by

$$\bar{r} = \int_0^\pi r(\theta) \sin\theta d\theta \quad (6)$$

where θ = linear angle measured from the normal to the detector face.

Although, in practice, the radiation field may not be isotropic, a reasonable approximation to this ideal can be created by accumulating the spectrum with the detector oriented in different directions, thus averaging out the angular dependence. In a typical room, this is accomplished by counting for equal lengths of time with the detector pointing at the floor, ceiling and each of the four walls. In effect, this is just each direction along three orthogonal axes. The same orientations would be required for outdoor measurements as well.

FLUX COMPUTATION

After performing the stripping routine, the resultant spectrum is converted to incident flux by applying the full absorption peak efficiency at each energy band. Thus,

$$\phi_i = \frac{N_i'}{\epsilon_{p,i} T}$$

where

ϕ_i = the flux incident in energy band i ($\gamma/\text{cm}^2\text{-s}$), and
 T = the accumulation time of the spectrum (min).

Although most of the spectrum is not actually comprised of peaks, it must be remembered that, at this point, each count represents a fully absorbed gamma ray. The continuum present is a result of scattered radiation from the media in which the detector is placed. In the case of an indoor measurement, this is just the room air, floor, ceiling, walls, furnishings, etc.

As in the case of r , the quantity $\epsilon_{p,i}$ must also be averaged over the entire 4π solid angle (eq. 6). Figure 3 shows an example of the angular response at one particular energy. As a function of energy, the angular correction factor for ϵ_p shows somewhat more variation than that for r , and was therefore calculated for each flux interval based on a curve fit to experimental data.

EXPOSURE RATE COMPUTATION

Having calculated the flux energy distribution, the exposure rate is given by:

$$I = 65.9 \sum_{i=1}^L \phi_i E_i \mu_{a,i} \quad (8)$$

where

- I = the gamma exposure rate ($\mu\text{R/h}$),
- E_i = the average energy of band i (MeV),
- $\mu_{a,i}$ = the mass absorption coefficient for air at energy E (cm^2/g), and
- 65.9 = numerical factor to convert from MeV/g-s to $\mu\text{R/h}$.

Due to electronic noise and reduced efficiency, the practical lower energy limit of this detector is about 0.05 MeV. Rather than extrapolate the spectrum below this energy, the lower summation index in the above equations was adjusted accordingly. In effect, the exposure rate is then only calculated for energies above 0.05 MeV. From available information on the spectral composition of typical environmental gamma radiation fields (Beck, 1972), we have determined that this lower energy cutoff results in only a 1% loss in exposure rate. Our results are therefore adjusted upwards by this small factor. Although the correction factor for indoor measurements would not be exactly the same, it is likewise expected to be small enough to warrant using the same value.

SAMPLE RESULTS

An example of a stripped indoor spectrum as compared to the original spectrum is shown in Figure 4. Typically, about 55 to 65% of the counts are removed. As can be seen, these counts are removed from the continuum portion of the spectrum, while the peaks due to the full absorption of primary flux are preserved. Although the accuracy of the results below 0.1 MeV begins to suffer due to uncertainties in the continuum shape and the ratio, r , the overall error in the final derived exposure rate is small because the contribution from this energy region is small. Despite such uncertainties, the accuracy of the measured flux energy distribution appears to be quite satisfactory, as is indicated by the comparison of measured and expected values for an infinite half-space source geometry (field location) presented in Table 1. The expected flux spectrum was calculated for the actual measured radionuclide concentrations in the soil using published spectral distributions

for this geometry that were derived with gamma ray transport methods (Beck, 1972). The favorable results obtained for this example leads us to believe that the overall stripping operation is sound and applicable to other source geometries as well.

The accuracy and sensitivity of this method are illustrated by the results of measurements made in a large 12 story warehouse building (see Table 2). As outlined before, an ionization chamber was used to measure the total exposure rate and the gamma estimate from the spectral strip method (using a 30 min count time) was then subtracted out to yield the cosmic component. The gamma component is seen to vary significantly from floor to floor. This was the result of varying wall composition. Likewise, the total exposure rate does not reflect any particular pattern. However, the inferred cosmic-ray contribution decreases relatively smoothly with depth in the building as expected. The 3.65 $\mu\text{R/h}$ result inferred in this manner for the roof of this building is within the range of reported values and in good agreement with the average value adopted for sea level (UNSCEAR, 1977). The marked change from the roof to the 12th floor is a result of the filtering out of the relatively soft electromagnetic component of the sea level cosmic ray flux. The remaining muon component is attenuated more slowly with depth in the building. The cosmic-ray values along the lengthwise fourth floor centerline demonstrate a rapid falloff with distance in from the building edge. This is consistent with the results of calculations that have been made for this same building and can be attributed to the highly peaked vertical direction of the cosmic-ray flux (Fujitaka, 1983).

The precision in the gamma exposure rate computed by this method was also tested by taking a series of 1 min spectra in a constant background gamma field of 5 $\mu\text{R/h}$. The standard deviation about the mean for the results was < 2%. In practice, longer counting times are used to achieve adequate statistics for photopeak analysis that may be performed as part of an overall radiation survey so that even better statistics would be expected under typical operating conditions.

CONCLUSION

The ability to measure the gamma exposure rate via the spectral stripping method described here is useful for situations where the source geometry and resultant spectrum are unknown. While a Ge detector and this method are not the only means to obtain an independent estimate of the gamma exposure rate in such situations, a high resolution spectrum can at the same time provide individual photopeak count rates which aid in the interpretation of the radiation field. When used in conjunction with an instrument such as a pressurized ionization chamber that provides a measure of the total exposure rate, this technique has proved to be valuable in conducting indoor radiation studies where separate estimates of the gamma and cosmic ray exposure rates are desired along with information on the relative contributions of the various natural radionuclides present (Miller and Beck, 1983). It is particularly useful for measurements in tall buildings where the cosmic ray component can vary significantly from its normal sea level value and cannot be easily predicted.

Since one of the intermediate results obtained in executing the stripping procedure is the energy distribution of the incident gamma flux, this method can also be used for situations where a knowledge of the spectrum in a particular radiation field is desired for the purpose of making energy response corrections to certain types of instruments.

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Table 1. Comparison of calculated and measured flux distributions for an infinite half-space.

Energy band (MeV)	Calculated Flux ($\gamma/\text{cm}^2\text{-s}$)					Total flux (%)	
	^{238}U series	^{232}Th series	^{40}K	^{137}Cs	Total	Calc.	Meas.
0.05-0.1	0.60	1.77	0.80	0.10	3.27	23.5	24.5
0.1 -0.15	0.35	1.31	0.56	0.07	2.29	16.5	16.5
0.15-0.3	0.51	1.77	0.72	0.09	3.09	22.2	24.3
0.3 -0.5	0.28	0.62	0.40	0.05	1.35	9.7	9.6
0.5 -0.9	0.23	0.85	0.32	0.12	1.52	10.9	9.6
0.9 -1.5	0.16	0.46	1.08	-	1.70	12.2	10.7
1.5 -2.0	0.07	0.15	-	-	0.22	1.6	1.6
> 2.0	0.02	0.46	-	-	0.48	3.4	3.2
Total	2.22	7.39	3.88	0.43	13.92	100.0	100.0

Note: Source concentrations and distributions are as follows:
 ^{238}U series 0.82 pCi/g uniform with depth
 ^{232}Th " 2.02 " " " "
 ^{40}K " 21.1 " " " "
 ^{137}Cs " 122 nCi/m² exponentially decreasing with depth;
relaxation length of 14 cm and soil density of 1.4 g/cm³

Table 2. Exposure rate measurements in a 12 story warehouse building.

Floor No.	Location	Exposure Rate ($\mu\text{R/h}$)		
		Gamma	Cosmic	Total
Roof	Center	5.28	3.65	8.93
12	"	5.82	2.35	8.17
10	"	4.36	2.32	6.68
8	"	4.37	2.11	6.48
5	"	5.66	2.02	7.68
4	"	6.73	1.59	8.32
2	"	6.84	1.34	8.18
Base.	"	7.00	1.00	8.00
4	Center-line 16 m in	5.25	1.55	6.80
4	Center-line 8 m in	5.02	1.87	6.89
4	Center-line edge	4.84	2.14	6.98
4	Corner	4.24	2.37	6.61

Figure 1. Distribution of counts in the continuum for normal incident 0.662 Me gamma rays and multiple step function approximation used in stripping operation.

Figure 2. Full absorption peak efficiency and total/peak efficiency ratio as a function of energy for normal incident gamma rays.

Figure 3. Full absorption peak efficiency and total/peak efficiency ratio as a function of incident angle for 1.25 MeV gamma rays.

Figure 4. Example of a spectrum before and after stripping operation.