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■ 論 文 ■

Determination of Spectrum-Exposure Rate Conversion Factor for a Portable High Purity Germanium Detector

Sang-Soo Kwak, Chong-Mook Park, and Seung-Gy Ro
Korea Advanced Energy Research Institute

ABSTRACT

A spectrum-exposure rate conversion operator G(E) for a portable HPGe detector used for field environmental radiation survey was theoretically developed on the basis of a space distribution function of gamma flux emitted from a disk source and an areal efficiency of the detector. The radiation exposure rates measured using this G(E) and the portable HPGe detector connected to a portable multichannel analyzer were compared with those measured by a 3" ϕ x 3" NaI(Tl) scintillation detector with the reported G(E) and a pressurized ionization chamber. A comparison of the three results showed that the result obtained using the HPGe detector was lower than those determined using the NaI(Tl) detector and ionization chamber by 17% to 29%, The difference obtained is close to that reported in literature.

The method developed here can be easily applicable to obtain a G(E) factor suitable to any detector for detecting the exposure rate of environmental gamma radiation, since the spectrum-exposure rate conversion operator can be calculated by a hand calculator.

1. INTRODUCTION

Environmental radiation is originated from radioisotopes in uranium and thorium decay series in ground soil, fallout produced by nuclear weapon testing and operation of nuclear facilities. If environmental radionuclides and radiation dose are evaluated accurately, the environmental effects due to operation of nuclear facilities can be well estimated. For accurate measurements of the environmental radiation dose and radionuclides, several investigators have studied detection techniques of the environmental radiation.

It is difficult to evaluate accurately the environmental radiation emitting from ground soil because the exposure rate of environmental radiation is not high enough to be detected. However, since germanium and NaI(Tl) scintillation detectors have good accuracy to a low level of radiation, the gamma ray spectrometric method using them is used for the measurement of the environmental radiation.

When the gamma ray spectometric method is used for measurement of dose, it is necessary to find the spectrum-exposure rate conversion operator for the detector to convert the measured gamma ray spectrum to exposure rate.

Moriuchi et al.[1] determined the spectrum-dose conversion operator, G(E), of NaI(Tl) scintillation detector and Terada et al.[2,3,4] determined the G(E) of Ge(Li) semiconductor detector.

Terada et al. assumed G(E) operator as polynomial function of a gamma ray energy E and found the coefficients in the polynomial function by the least squares curve fitting method. Moriuchi et al. calculated the value of G(E) in sequence from the determined values of G(E) at lower energies, based on a square pulse height distribution function. But an actual pulse height distribution is not a square rectangular distribution and therefore a computer was used to obtain a precise dose estimation.

In this study, a mathematical method for determination of G(E) operator is proposed. In this method a distribution function of standard point sources and an areal efficiency equation proposed by Cutshall et al.[5]are used.

For validation of the G(E) operator for high purity germanium detector (HPGe) proposed here, the exposure rates of environmental radiation emitted from ground soil were determined using HPGe detector facing down at the hight of 1 meter above the ground with the determined G(E) and evaluated by comparison with exposure rates measured by $3''\phi$ x $3''$ NaI(Tl) scintillation detector with the G(E) factor determined by Moriuchi et al. and a pressurized ionization chamber (RSS-111) which is a continuous environmental radiation monitor located at the center of KAERI area.

2. CALIBRATION OF HPGe DETECTOR

A portable multichannel analyzer (Canberra Series 10) connected to a portable high purity germanium detector was used in this work. Detailed specifications of the detector were given in Table 1, and the standard radiation sources used were Am-241(0.06MeV), Ba-133(0.356MeV), Cs-137 (0.662MeV), and Co-60(1.332MeV).

When the exposure rate due to the environmental radiation emitted from ground soil is measured at the height of 1 meter above the ground, the ground soil can be treated as an infinite plane source.

Therefore, to simulate the environmental plane source and to reduce the effects of foreign radiation sources for determination of the efficiency of the detector, the portable detector was placed on a table 1 meter away from the pole standing straightly up on the floor in laboratory with facing the pole as shown in Fig. 1. Each of standard sources was placed on the pole and moved from the center of the circular view of the detector to the outside 120 cm of radius of the circular view by 10 cm interval along a vertical direction.

Each of sources at every position was counted for 1000 seconds.

Table 1. Specification of high purity germanium detector.

Specification of Detector	Relative Efficiency : 10.0% Resolution : 2.0Kev FWHM(1.33MeV Co-60) 0.77KeV FWHM(0.77MeV Co-57) Geometry : Closed Ended Coaxial Diameter : 47.6mm Length : 32mm Active Area : 17.9cm^2 Distance from Window : 5mm

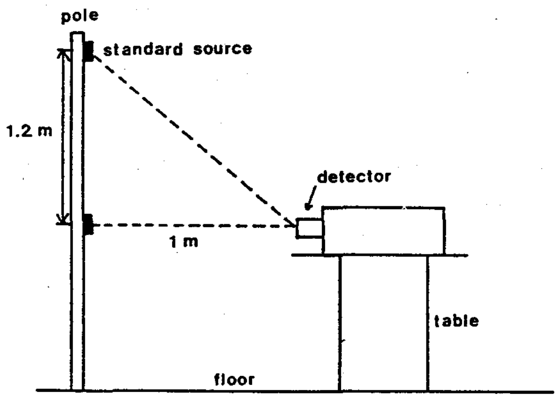

Fig.1. Detector and standard sources mounting configurations for the calibration of HPGe detector.

3.DETERMINATION OF SPECTRUM-EXPOSURE RATE CONVERSION OPERATOR G(E)

3.1. Determination of G(E)

The exposure rate of any gamma spectrum is obtained by applying a conversion factor to a gamma specturm and therefore a relation between a distribution function of the gamma ray pulse height detected for various energies of gamma rays and total exposure rate is given as [6-9] :

$$\dot{X}=\int_{0}^{\infty} N(E)\ G(E)dE \qquad (1)$$

Where G(E) = gamma ray energy dependent operator for converting the gamma ray spectrum to exposure rate, μR/h/cps,

N(E) = gamma ray energy dependent gamma ray distribution detected by detector, counts/sec, and

$\dot{X}$ = total exposure rate, μR/h.

N(E) in Eq.(1) is a continuous function of energy and can not be measured by a single spectrometer. What is measured by the spectrum is a quantity

$$N_i=\int_{E_i}^{E_{i+1}} N(E)dE \qquad (2)$$

where $E_{i+1}-E_i=\Delta E_i$ is an energy "bin" of the spectrometer which represents energy interval or the width of one of the channels for a multichannel analyzer, and N_i represents number of gamma rays detected in the i-th energy interval. Hence, with an assumption of the mean energy used for the conversion operator, Eq.(1) can be written as :

$$X=\Sigma\ N_i\ G(\bar{E}_i) \qquad (3)$$

where $\bar{E}_i$ = mean energy in the i-th energy interval.

Eq.(3) represents a conversion equation for converting gamma ray specturm to exposure rate of gamma ray flux of energy E_i at detection position is given as [10] :

$$\dot{X}_i=65.664\ \phi_i\ \left(\frac{\mu_a}{\rho}\right)^{air} E_i \qquad (4)$$

where $\dot{X}_i$ = exposure rate of gamma ray of energy E_i, μR/h

ϕ_i = gamma ray flux of the i-th channel at detection position, γ rays/cm² sec

$\left(\frac{\mu_a}{\rho}\right)^{air}$ = mass absorption coefficient in air, cm²/g, and

E_i = mean gamma ray energy of the i-th channel, MeV.

Gamma ray flux at distance R cm away from a disk source with radius R_e cm and the strength of the source S_i(dps/cm²) is given as follows[11] :

$$\phi_i=\frac{S_i}{2}\int_{R}^{\sqrt{R^2+R_e^2}} \frac{e^{-\mu r}}{r}dr \qquad \cdots\cdots (5)$$

where R_e is equivalent to the radius of an area to be effectively detected and the integral in Eq.(5) can be computed by numerical method.

If the areal efficiency of a detector is known, the source strength S_i can be computed from N_i as :

$$S_i = N_i / F_i \qquad (6)$$

where F_i is the areal efficiency of a detector for detecting the gamma ray of energy E_i within an area of radius R_e to be effectively detected.

From Eqs. (4), (5) and (6), the total exposure rate of gamma ray emitted from the disk source can be calculated as follows :

$$\dot{X} = \sum_i 65.664 \left(\frac{\mu_a}{\rho}\right)^{air} \frac{E_i N_i}{2F_i} \int_R^{\sqrt{R^2+R_e^2}} \frac{e^{-\mu r}}{r}\, dr \cdots\cdots\cdots (7)$$

Comparing Eqs. (3) and (7), Eq.(8) is obtained.

$$G(E_i) = 65.664 \left(\frac{\mu_a}{\rho}\right)^{air} \frac{E_i}{2F_i} \int_R^{\sqrt{R^2+R_e^2}} \frac{e^{-\mu r}}{r}\, dr \cdots\cdots\cdots (8)$$

The conversion operator $G(E_i)$ given by Eq.(8) is used for converting the gamma ray spectra to exposure rate. Namely, if the areal efficiency F_i of detector for a gamma ray energy E_i is known, the conversion factor of that gamma ray at the height of R above the ground can be calculated by Eq.(8).

3.2. Determination of Areal Efficiency of HPGe Detector for a Planar Source

A basic method to determine the areal efficiency of a detector for detecting radiation in open field was presented by Cutshall et al.[5]. Their method was applied in this study with a slight modification in the term representing the energy dependence of the efficiency at zero radius in the point source response equation, Eq.(3), in their report as follows :

$$\mathfrak{R} = \{a - b\exp(-c/E^d)\}\ \exp(-kr^2) \cdots\cdots\cdots (9)$$

$\mathfrak{R}$ is a point source response as a function of energy E and radius r of the point source position away from the center of circle of view of the detector. The constants a, b, c and d in Eq.(9) are in connection with the efficiency of the detector at a radius of zero and are obtained 4.98×10^{-5}, 4.61×10^{-5}, 0.2 and 2.1, respectively, by fitting the point source response data obtained at zero radius to an exponential function shown in Fig. 2 by a non-linear least squares curve fitting method.

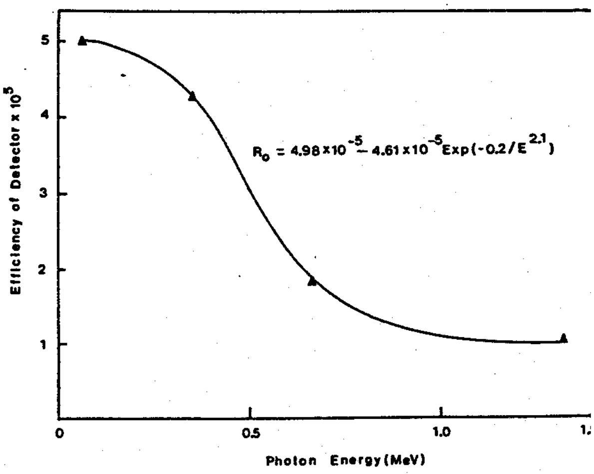

Fig.2. Energy dependence of the efficiency of HPGe detector at zero radius.

The obtained equation is satisfactorily fitted to the data. The exponential function shown in Fig. 2 is the same as used in Reference 12.

The constant k is related to the shapes of response curves with radius. The observed point source responses of the detector plotted in Fig.3 were obtained by detecting point sources placed in the circle of view and fitted by the least squares curve fitting to obtain the mean value of k, 1.945×10^{-4}. The areal efficiency of the detector for a planar source could be theoretically obtained by integrating Eq.(9) over the circle of view of the detector with respect to the radius r as indicated by Cowdrey[13].

The modified final form of the areal efficiency of the detector for the area to be effectively detected given as follows :

$$F_i = \pi\ \{a - b\exp(-c/E_i^d)\}\ \{1 - \exp(-kr^2)\}/k \qquad (10)$$

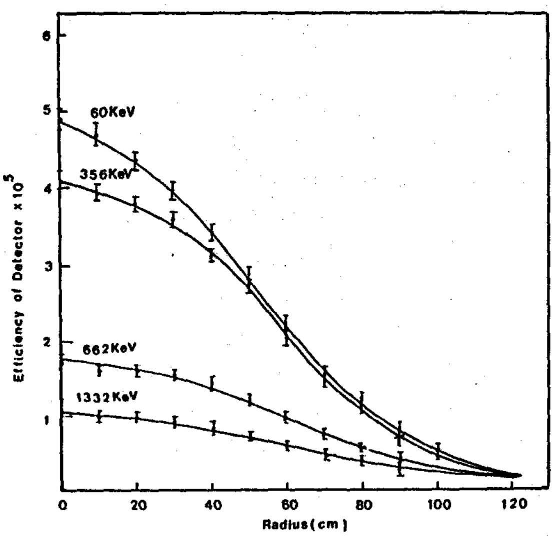

Fig.3. Curves showing point sources efficiency of HPGe detector as a function of radius for several gamma ray energies.

where F_i = effective areal efficiency of the detector for the gamma ray of energy E in counts per disintegration per ㎠ as defined earlier.

The constants a,b,c,d and k in Eq.(10) are given above. Eq.(10) represents the areal efficiency for a planar source that is uniformly distributed 1 meter below the detector.

For the determination of the areal efficiency of the detector using Eq.(10), an effective radius R_e of the circular area to be detected for any given gamma ray energy must be decided first. The effective radius is defined as a limit of radius of a circular area to be effectively detectable so that the radiations emitted outside of the effective area do not contribute much to the detection of the detector.

Hence, the areal efficiency of the detector to detect the area within the effective radius can be fractionally obtained from the total areal efficiency for the infinitive area as follows :

$$\frac{F_i}{F_i^{\infty}} = 1 - \exp(-kR_e^2) \cdots\cdots\cdots\cdots\cdots\cdots (11)$$

where superscript ∞ denotes "infinitive".

Eq.(11) shows that the fractional areal efficiency of the detector to the infinitive areal efficiency is not dependent on gamma ray energy but a function of the radius of the detectable area. The fractional areal efficiency was chosen to be 0.99 and then the determined effective radius was 154cm from Eq.(11).

Therefore, the areal efficiency for the detection of the area of the effective radius 154cm is given as a function of gamma ray energy as follows :

$$F_i = 0.796 - 0.737\exp(-0.2/E_i^{2.1}) \cdots\cdots\cdots\cdots\cdots\cdots (12)$$

The areal efficiency of the detector for the gamma ray energy E emitted from the ground soil within circle of the radius of 154cm can be computed using Eq.(12).

4. EXPOSURE RATE CALCULATION PROCEDURE

Before the calculation of the exposure rate of the gamma ray, the value of the integral for the effective radius 154cm of the detectable area included in G(E_i) operator given in Eq.(8) must be first determined. To do this, the integral was numerically integrated for a given air attenuation coefficient of a gamma energy E in the range of 0.01MeV to 3MeV, and plotted as a function of the gamma energy as shown in Fig.4.

For the calculation of exposure rate detected by HPGe detector, the net number of counts of each peak for a gamma ray energy E_i is obtained from the gamma ray spectrum and set to N(E_i), and next the value of the integral in G(E_i) operator and the areal efficiency F_i for E_i are obtained from Fig.4 and Eq.(12), respectively. Then, the conversion factor of the gamma ray energy E_i is calculated by Eq.(8). Finally, the exposure rate $\dot{X}_i$ of the gamma ray of energy E_i can be calculated by multiplication of N(E_i) and G(E_i), and the summation of $\dot{X}$ for all peaks of gamma

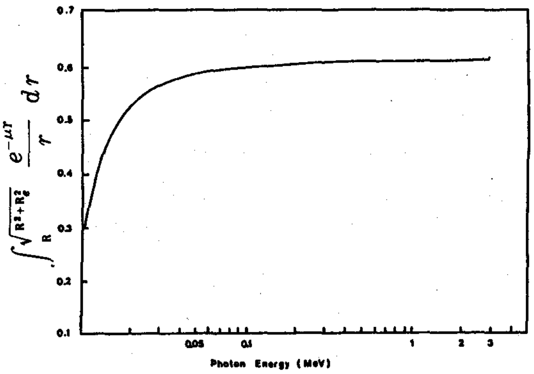

Fig.4. The value of integral of Eq.(8) as a function of photon energy.

ray spectrum represents the total exposure rate of the radiation emitted from the ground soil at the measuring point.

For the calculation of the exposure rate by the NaI(Tl) detector, the calculation procedure used in reference 14 is employed. The total energy range of the gamma spectrum is devided into small energy intervals.

The net count rate within each interval is taken and multiplied by the conversion factor of the mean energy of the energy interval to determine the exposure rate X_i. The exposure rates for all energy intervals are summed to obtain total exposure rate.

5. In-Situ GAMMA SPECTROMETRY

In-situ gamma spectrometry for the measurement of the environmental radiation was conducted at KAERI area. The detector used in this study was a closed ended coaxial type HPGe detector. A 3" ϕ x 3" NaI(Tl) scintillation detector was used for comparison of the exposure rates determined by HPGe detector with those of the NaI(Tl) scintillation detector to evaluate the conversion operator G(E) developed in this study. A pressurized ionization chamber (RSS-111) was also used to verify the exposure rates measured by HPGe and NaI(Tl) detector.

The HPGe detector was set up on a tripod 1 meter above the ground in open field with facing down and connected to the portable multichannel analyzer and then NaI(Tl) scintillation detector was set up by the same way after finished the detection by HPGe detector. The detectors on the tripod was separated about 1 meter away from the ionization chamber.

The data were collected for 2000 seconds. To plot the spectrum of the detected radiation, the collected data were recorded on magnetic tapes which were returned to a plotting system.

6. RESULTS AND DISCUSSION

The values of G(E) determined were plotted as a function of gamma ray energy in Fig.5 and compa-

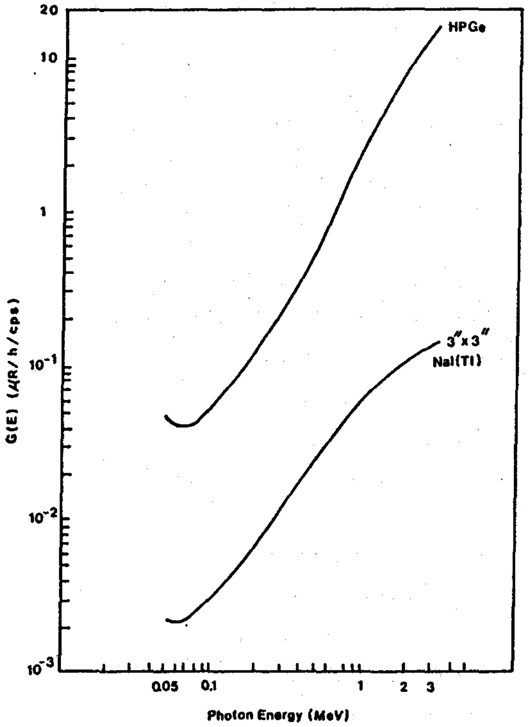

Fig.5. Comparison of G(E) between HPGe detector used in this study and 3"ϕx3" NaI(Tl) detector.

red with the reported values of G(E) for 3"ϕx3" NaI (Tl) scintillation detector [1]. The shape of curves of G(E) determined for the portable HPGe detector used in this study is very similar to that previously reported for NaI(Tl) detector. The energy range of gamma-ray used in calculation of G(E) was 0.05 MeV to 3 MeV as indicated in References 15 and 16.

The gamma ray spectrum collected by the HPGe detector was shown in Fig. 6. Identified radionuclides in the ground soil were K-40, fallout Cs-137 and daughters of U-238 and Th-232. Fig. 7 shows the gamma ray spectrum collected by the 3"ϕx3" NaI(Tl) scintillation detector. Figs. 6 and 7 were used for the calculation of the total exposure rate.

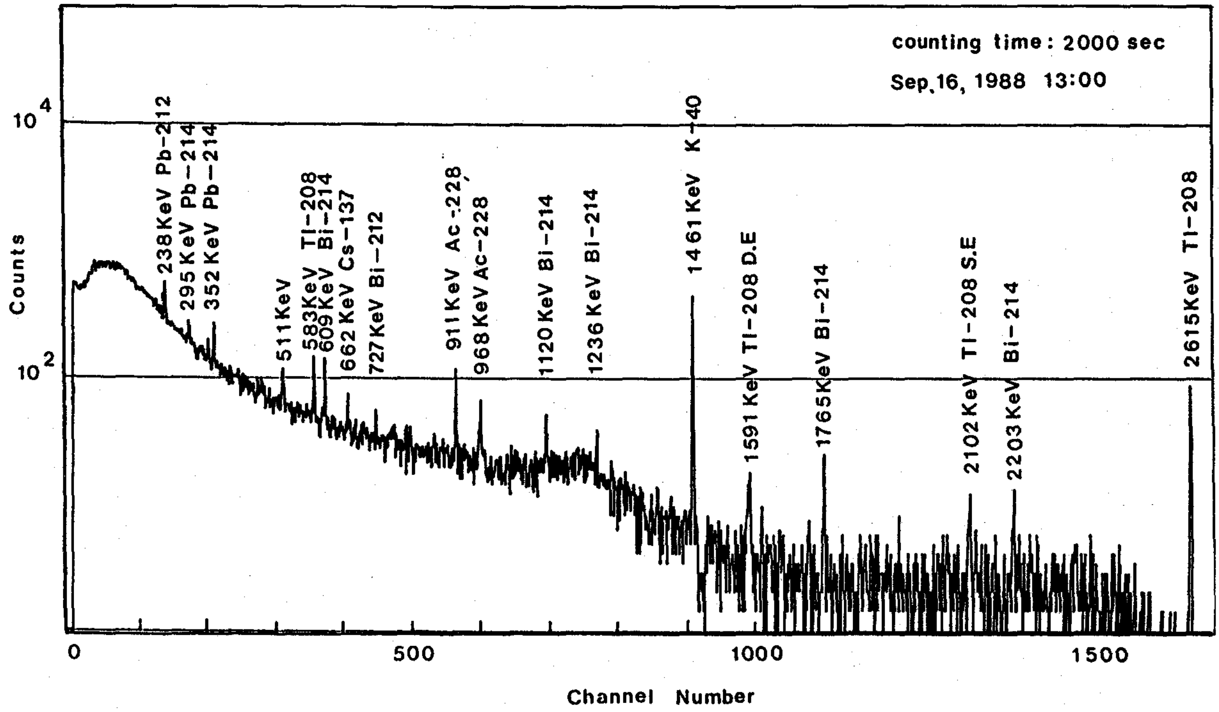

Fig.6. In-situ gamma ray spectrum measured by HPGe detector on the lawn at KAERI area on Sep. 16, 1988.

By following the calculation procedure described earlier, the net spectrum of the peaks detected by the HPGe detector system, the conversion factors of the corresponding peak energies, and their exposure rates were determined from Figs 5 and 6, and Eq.(3), respectively, and tabulated in Table 2.

The net spectra are the number of the unscattered radiations detected, and therefore the individual exposure rates of the isotopes present in ground soil are due to unscattered radiations, which are given in Table 2.

The summations of the individual exposure rates are the total exposure rates of all unscattered radiations emitted from the ground soil at the hight of 1 meter above the ground which are 8.25±0.25μR/h, 7.54±0.24μR/h, and 7.96±0.29μR/h at 1 : 00, 2 : 00, and 3 : 00 PM, respectively.

The spectrum, shown in Fig. 7, detected by 3"ϕx 3" NaI(Tl) detector was also converted to the exposure rate using the corresponding G(E) factor obtai-

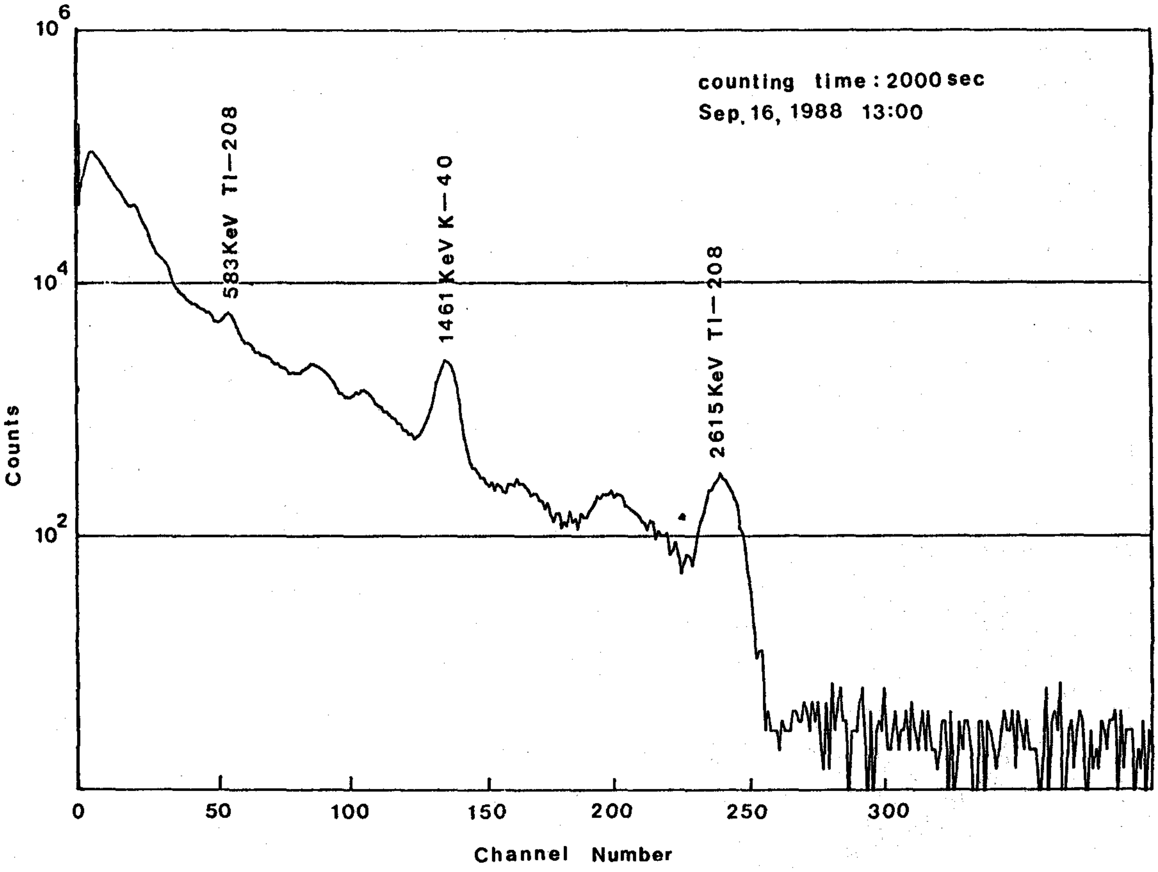

Fig.7. In-situ gamma ray spectrum measured by 3″ϕx3″ NaI(Tl) detector at the same location and time as measured by HPGe detector.

Table 2. Net Spectum, conversion factor, and exposure rate of radionuclides in the ground soil detected by HPGe detector at 1 meter above the ground.

Nuclide	Energy 〔KeV〕	G(Ei)	N(Ei) 〔x10^3〕			D(Ei) 〔μR/h〕		
			1:00	2:00	3:00	1:00	2:00	3:00
Uranium Series								
Pb-214	295	4. 21	50	101	119	0. 01	0. 02	0. 02
	352	0. 29	165	81	135	0. 05	0. 02	0. 04
Bi-214	609	0. 91	140	116	109	0. 13	0. 10	0. 10
	1120	3. 60	75	41	31	0. 27	0. 15	0. 11
	1236	4. 25	31	12	37	0. 13	0. 05	0. 16
	1765	8. 20	29	37	41	0. 24	0. 30	0. 34
	2203	11. 80	13	7	11	0. 15	0. 08	0. 13
Thorium Series								
Pb-212	238	0. 16	437	365	442	0. 07	0. 06	0. 07
Tl-208	583	0. 81	213	141	139	0. 17	0. 11	0. 11

Table 2. (continued)

Nuclide	Energy [KeV]	G (Ei)	N (Ei) [x10^3]			D (Ei) [μR/h]		
			1:00	2:00	3:00	1:00	2:00	3:00
	1591	7.00	38	23	15	0.27	0.16	0.10
	2102	11.00	17	18	12	0.19	0.20	0.13
	2615	14.50	138	132	125	2.00	1.91	1.81
Ac-228	911	2.32	164	128	163	0.38	0.30	0.38
	968	2.65	55	78	167	0.15	0.21	0.44
Bi-212	727	1.32	47	40	55	0.06	0.05	0.44
K-40	1461	6.00	653	631	652	3.92	3.78	3.91
Cs-137	662	1.05	55	36	42	0.06	0.04	0.07
Total						8.25	7.54	7.96

Note : For calculation of conversion factor, the air density used was 0.001205g/cm^3 at 20℃.

ned from Fig.5, as followed the calculation procedure for the NaI(Tl) detector. The total exposure rates at different time were 10.74±0.02μR/h, 10.66±0.02μR/h and 10.65±0.02μR/h, which included the effects of cosmic rays and gamma ray emitted from K-40 containg in the optical window of NaI(Tl) detector [17]. Their contributions to the exposure rate are known to be 0.23μR/h and 0.18μR/h, respectively, and other factor affecting NaI(Tl) detector is a detection response due to photon incident direction, which is about 0.94 for 3"ϕx3" MaI(Tl) detector [17]. Applying these correction factors, the resultant true exposure rate detected by 3"ϕx3" NaI(Tl) detector at different time within a day were 9.71μR/h, 9.63μR/h, and 9.62 μR/h.

From the ionization chamber the obtained exposure rate over the detection period at different time were 13.13±0.48μR/h, 13.33±0.49MR/h R/h, and 12.74±0.46μR/h which include effects of the cosmic ray effects, since the exposure rate of the cosmic ray is known to be 3.59μR/h at 1 atmosphere pressure [18], the true exposure rate detected by the ionization chamber were 9.54±0.48μR/h, 9.47±0.49μR/, and 9.15±0.46μR/h at different time.

The exposure rates obtained by three detectors were tabulated in Table 3 and to compare them, the error deviations were included in the determined exposure rates.

A comparison of three results showed that the results obtained using the HPGe detector were lower than those determined using the NaI(Tl) detector and ionization chamber of which the results were close to each other.

The authors believe that the differences may be

Table 3. Comparison of exposure rates due to environmental gamma ray detected at KAERI area by three methods on Sep. 16, 1988.

Detector	Exposure Rate (μR/h)		
	1 : 00PM	2 : 00PM	3 : 00PM
HPGe Detector	8.25±0.25	7.54±0.24	7.96±0.29
3"ϕ×3"NaI(Tl)	9.71±0.02	9.63±0.02	9.62±0.02
Ionization Chamber	9.54±0.48	9.74±0.49	9.15±0.46

Note : The deviations of detection error by ionization chamber were determined using ±5% error of the detector given in the description manual.

caused by the results for the in-coming scattered radiations to be excluded in the exposure rate determined by the HPGe detector but included in those determined by the NaI(Tl) detector and ionization chamber.

The differences between them were in the range of 17% to 29%, and can be compared with the reported difference of 15%[3]. From this comparison one can understand that the G(E) operator for HPGe detector developed in this study is a reliable spectrum-exposure rate conversion operator.

7. CONCLUSION

The G(E) operator theoretically developed in this study, based on a space distribution function of a point source and an areal efficiency of a detector, was proved to be a reliable operator applicable to the measurement of the environmental radiation exposure rate of gamma radiation emitted from the ground soil.

The advantage of the method developed here, compared to any other method reported, is to simply obtain a G(E) operator suitable to any detector from which a spectrum-exposure rate conversion operator can be calculated by a hand calculator.

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휴대형 고순도 게르마늄검출기에 대한 스펙트럼-조사선량율 변환연산자의 결정

곽상수 · 박종묵 · 노성기
한국에너지연구소

요 약

환경방사선 측정에 이용되는 휴대형 고순도 게르마늄검출기에 대한 스펙트럼-조사선량율 변환연산자를 원판형선원의 공간분포함수와 검출기의 평면에 대한 측정효율식을 적용하여 이론적으로 유도했다. 이와 같이 구한 변환연산자와 휴대형 고순도 게르마늄검출기를 이용해 한국에너지연구소내에서 방사선 조사선량율을 측정했다. 측정한 조사선량율을 이미 알려진 3"φx3"NaI(Tl) 섬광검출기에 대한 변환연산자를 적용해 NaI(Tl)검출기로 측정한 조사선량율과 가압형 이온전리함으로 측정한 값과 비교했다. 고순도 게르마늄 검출기로 얻은 결과는 NaI(Tl) 검출기와 가압형 이온전리함으로 얻은 값보다 약 17-29% 낮음을 보여주었다. 이 차이는 다른 문헌에서 보인 차이와 거의 같았다.

본 논문에서 제시한 스펙트럼-조사선량율 변환연산자는 탁상용 계산기로 쉽게 계산할 수 있으며 환경방사선의 측정에 사용되는 여러 검출기에 대해서도 쉽게 적용할 수 있는 장점이 있고 지각에서 방출되는 각 핵종별로 조사선량율을 구할 수 있는 장점이 있다.