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Abstract, Construction of a Ge-BGO Compton Suppression Gamma-ray Spectrometer and Its Application to Environmental Samples, Part 1: The System of the Spectrometer and Its Basic Performance, In order to develop a very high sensitive Ge gamma-ray spectrometer, a Compton suppression gamma-ray spectrometer with a BGO guard detector system has been constructed. The BGO detector system detects 88% of the gamma-rays from $^{60}$Co that are committing to the principle of the suppression system. Peak-to-Compton ratio for the 661 keV gamma-rays from $^{137}$Cs has been improved from 128 to 786 with the Compton suppression spectroscopy. By the development of the spectrometer the minimum acceptable radioactivity of $^{137}$Cs has been improved from 0.091 Bq to 0.044 Bq with the coefficient of variation of 3%.

This work has been carried out as the one of the activities of "Lecturer/Instructor Exchange Program between ETC, BATAN and NuTEC, JAERI" under the agreement "Nuclear Human Resources Development between BATAN and JAERI".
Introduction

A research, development and utilization of nuclear energy should not be accepted without any programs to ensure and maintain nuclear safety. Nuclear spectrometry technique is widely used as one of the useful techniques to maintain natural environment and to assure safe normal operation of nuclear facilities.

High sensitive gamma-ray spectrometers have been applied to nuclear laboratories from the standpoint of radiation protection and to diagnoses of nuclear facilities such as nuclear power plants and radioactive-waste management facilities from standpoint of nuclear safety taken the maintenance of natural environment into consideration.

The deeply analyzed measurements results can be fed back to improve the facilities and natural environment and they will contribute in getting acceptance of nuclear utilization by the general publics and to promote development of nuclear technologies.

It is essential to reduce background level for improving instrumental sensitivity of radioactivity, especially in low level counting.

Suppression of Compton continuum will be the most effective method to reduce the background in the region of full-energy peaks in multichannel analyzer spectra.

With a view toward development of a high sensitive Ge gamma-ray spectrometer, mainly intending for the detection of $^{137}$Cs in natural environment, and for the leachability test of $^{137}$Cs in radwaste management facilities, a Compton suppression Ge gamma-ray spectrometer has been constructed. A BGO (Bismuth Germanate) of the composition Bi$_3$GeO$_5$ scintillation detector system has been used as a Compton suppression detector.

Due to the high atomic number (Bi: 183) and high density (7.13 g/cm$^3$), BGO scintillation detectors are the most efficient gamma-ray detectors now in use. They are recommended for use as a Compton suppression detectors.

Therefore, it is expected that this spectrometer system achieves an appreciable suppression of Compton background. i.e. makes possible to detect further lower level of radioactivity of $^{137}$Cs compared with the achievable level by the usual (single) mode of this spectrometer.


In the Compton suppression Ge gamma-ray spectrometer constructed in this work, the Ge detector is surrounded by BGO detector system. The signals from the Ge detector have been rejected at a linear gate circuit in anti-coincidence mode by the signals, which are generated in the Ge detector and tile BGO detector system at the same time. In other words, the linear pulses of the Ge detector are rejected at a linear gate circuit by the coincidence pulses of the outputs of two timing single channel analyzers for the Ge and BGO detectors.

1.1. Configuration of the Ge-BGO Detector System

Simplified drawing of the arrangement of the Ge detector and Compton suppression EGO detectors is shown in Fig. 1.

1.1.1 HP Ge Detector

Manufacturer: Princeton Gamma-Tec Inc. (USA)
Model: IGC 40195, SeT.No.: 2631
Detector Geometry: p-type Coaxial Crystal
Size: 13 nun in diam., 59 nun in length
Active Volume: 176 cm$^3$
Dead layer: 1 nun
Detector/Window Distance: 5 mm
Relative Efficiency: 40.1X
FWHM: UQ keV at 1332 keV ($^{60}$Co).
X60 eVat 122 keV ($^{57}$Co)

1.1.2 HGD Detector System

For synthesizing low-background EGO crystals, bismuth compound (Bi$_3$O$_3$) of the lowest radioactive contamination has been chosen, especially avoiding the contamination of $^{111}$InBi that is one of fallout-nuclides caused by nuclear testing. The radioactive concentration of $^{117}$MBi in the Bi$_3$O$_3$ used for the crystals is less than 2X
The background count-rate of the BGO detector system resulting from the contamination is less than 2 counts per second, which is less than 1X compared to the most contaminated one.

(a) Main BGO Detector

The main BGO detector is annulus-type crystal for detecting side- and back-scattered gamma-rays from the Ge detector, into which the Ge detector is inserted.

Manufacturer: Cismatec (France)
Model: EES-Model V
Crystal Shape: Annulus
Crystal Size: External Diam.: 83.2 mm
       Internal Diam.: 80.2 mm
       Length: 200 mm
Crystal Thickness: 50 mm
Aluminum Diameter: 83.2 mm
Crystal Weight: 29.78 kg
Housing Thickness: 1.5 mm aluminum
FWHM: Better than 20% (661 keV: 137Cs)
Notes: Seven optically independent side elements BGO crystals with seven photomultipliers of 2 inch diameter

(b) Plug BGO Detector

The plug BGO detector is solid cylindrical crystal for detecting back-scattered gamma-rays from the Ge detector. The plug BGO detector is inserted into the annulus of the main BGO detector in usual uses.

Manufacturer: Cismatec (France)
Model: EEP-Model V
Crystal Shape: Solid Cylinder
Crystal Size: 70.2 mm diam. x 76.2 mm
Crystal Weight: 2.65 kg
Housing Thickness: 0.8 mm aluminum
FWHM: Better than 13% (661 keV: 137Cs)
Notes: One photomultiplier of 3 inch diameter

(c) Back-catcher BGO Detector

Manufacturer: Cismatec (France)
Model: EEC-Model V
Crystal Shape: Annulus separated into 1st half and 2nd half for surrounding the dip-stick of the Ge detector
Crystal Size: External Diam.: X(U 11111111

1.1.3 Shielding of the Ge-BGO Detector System

The Ge-BGO detector system is shielded by low-background lead in thickness of 10 mm. The inside of the lead shield is lined with low-background oxygen-free copper in thickness of 5 mm and Lucite in thickness of 0.2 mm.

1.2 Arrangement of the Electronic Units

Block diagram of the electronic system of the Ge-BGO Compton suppression gamma-ray spectrometer is presented in Fig. 2. The input pulse width and anti-coincidence gate pulse width of the anti-coincidence circuit is 0.5 μs and 5 μs respectively. Shaping time constant of 50 μs has been set for the spectroscopy amplifier of the HP Ge detector.

1.2.1 Linear/Logic Pulse System of the 111 Ge Detector

Preamplifier: PGT RG 11B/C
Spectroscopy Amplifier: Canberra 1413
Linear Delay: ORTEC 427 A
Pulse Height Adjuster (No. 1 Input of SUII Amplifier): Canberra 1465A
Timing Single Channel Analyzer: ORTEC 551
1.2.2 Linear Logic Pulse System or the BGO Detector System

Sun for Each BGO: Three Channel Preamplifier/Line Drivers. Cyberstar (France) EES-VIEEC-V
Sum Amplifier: Three Channel Sum-Shaping Base Line Restorer Amplifier (Gaussian 1 us fixed peaking time). Cyberstar CSY-4SA
Timing Single Channel Analyzer: ORTEC 455
Gate/Delay Generator: ORTEC 416A

1.2.3 Logic System for HP Ge and EGO Systems

Anti-Coincidence: ORTEC V14A
Gate/Delay: ORTEC V14A
Linear Gate/Stretcher ORTEC 542

1.3 Multichannel Analyzer and Data Processor

Multichannel Analyzer: Seiko EG&G 7X(1) with two Analog-to-Digital Converters (Seiko 1X20)
Data Processor and Output Machines: NEC PC YX(1) YX with a Software/Data Base by Seiko. Plotter (Roland) and Line Printer (NEC)


The performance of the Ge-BGO Compton suppression gamma-ray spectrometer has been examined by the measurements with the representative parameters characterizing gamma-ray spectrometers such as energy resolution, detection efficiency, peak-to-Compton ratio, peak-to-total ratio, Compton suppression factor, natural background level, etc.

Minimum acceptable radioactivities of the Ge-BGO Compton suppression gamma-ray spectrometer has been evaluated for 137Cs and 60Co as shown in Figs. 4 and 5. and the results of FWHM and peak-to-total ratio are tabulated in Table I, together with the results shown in Fig. 3.

Errors in Table I are statistical standard deviation.

The result of Table I clarifies that the peak-to-total ratio of 3 inch diam. x 3 inch BGO detector is 1.21 times or that of the same size NaI(Tl) crystal of the same sizes. resulting from its high atomic number and density.

Energy resolution of the BGO detector system becomes poor when the source position in the annulus becomes far from the photomultipliers of main BGO, which is mainly due to the decrease of light collection efficiency at the photocathodes and the increase of attenuation of light in BGO crystal.

2.2 Performance of the HP Ge Detector

The certified values of the HP Ge detector by the manufacturer. UQ keV of FWHM and 46.1% of relative efficiency have been satisfied at the initial measurement without meaningful differences.

Three years after the initial measurement, measurements of pulse height distributions with the HP Ge detector as the Ge-BGO system shown in Fig. 2 have been done, in the measurements. points sources of


as Cs. 

mixed nuclides of $^{137}$Cs, $^{141}$Ce Cs and e-xTh have been used in both spectroscopy modes of the single (normal) and Compton suppression. The results of the measurements are shown in Figs. (A, 7A and X. It is apparent that the pulse height distributions of Figs. (A and 7A are recording the events of scattered gamma-rays from the BGO detector system, which are seen as the increase of the Compton continua like a steps at around the energy of U;o° back scattered gamma-rays.

The pulse height distributions featuring Compton spectra of the Figs. (A and 7A are shown in Figs. (B and 7B, in which the energy regions used for averaging Compton continuum needed to calculate peak-to-total ratios are indicated. In particular, Fig. 7B illustrates apparently the single and double escape peaks of the 1332 keY from $^{60}$Co as well as the effective reduction of Compton continuum.

### 2.2.1 Energy Resolution

Measurements of energy resolution of the HP Ge detector for 1332 keV ($^{60}$Co) and 141 keY (Ir Cs) have been made with the ADC of conversion gain of xk channels. The results are shown in Table 2, together with the ratio of FWTM/FWHM.

Any observable difference of FWHM has not been observed between the single and Compton suppression modes.

The results of Table 2 shows that FWHM for U32 keY is broadened by 1(eV compared to the initial value with the simplest electronic arrangement.

The ratios, FWTM/FWHM indicate that the profile of full-energy peak can be fitted with Gaussian distribution quite well, because of that the ratios agree with the theoretical value of 1-n (HWTM/HWHM = -1/a2.35cr. where a is standard deviation).

### 2.2.2 Detection Efficiency

The 25 cm relative efficiency of the HP Ge has been tested, and no appreciable change, i.e. more than 1% in the efficiency has been observed.

Intending to obtain full-energy peak efficiency for volume samples, three volume sources containing $^{141}$Cs, $^{137}$Cs, $^{137}$Ir and/or $^{137}$xTh have been prepared with use of induced and natural radioactivity.

Density of the sample ranges widely from 0.347 g/cm² to 1.50 g/cm², depending on the sample.

The diameter and the thickness of the sample is 75 mm and 34±1 nun, respectively depending on the sample. The sample container is made of Lucite of 1 nun in wall thickness.

In the measurements, the samples are attached directly to the detector window (sample-to-window distance. SD: 3 nun) of horizontal type dipstick. Full-energy efficiencies obtained by the measurements with single and Compton suppression modes are listed in Table 3, and the result measured with the single mode is shown in Fig. 9 as a function of gamma-ray energy, in which the correction for coincidence sum effect has not been applied.

In Fig. 9 the error bars are fixed at 11.4%, which are three standard deviations of $^{141}$Cs.

It is seemed to be that the efficiencies of 04 keY and 795 keY from U4Cs is suppressed, more or less. by coincidence sum effect.

In Table 3 the ratio of the full-energy peak efficiency in the single mode (-$^{141}$Ir Cs and $^{141}$K is unity in both mode, i.e. any change in the efficiency has not been observed.

Contrary to single gamma-ray emitters, the ratios for the gamma-ray emitted from multiple gamma-ray emitters, $^{141}$Cs, $^{60}$Co and $^{137}$xTh, increase drastically far beyond unit, i.e. the full energy peak efficiencies decrease drastically in the Compton suppression mode by the cascade-gamma effect.

The large value of these ratios proves that the sum of the total detection efficiency of the BGO detector system for the
associated gamma-rays with the gamma-ray concerned, i.e. the gamma-rays belonging to the same cascade as the gamma-ray concerned is very high.

From the ratios listed in Table 3, the sum of the total detection efficiency of the BGO detector system for the associated gamma-rays including the scattered gamma-rays of the gamma-rays concerned in the Ge detector, but can be calculated as 95.9±1%, for 134Cs, 87.5±1%, for 60Co and 94±1.7% for 61Irr from the following relationship.

\[ \frac{E_{bk,b}}{E_{bk,c}} = 1 - \left( \frac{E_{bk,c}}{E_{bk,b}} \right)^{-1} \]

Energy and its abundance of gamma-rays concerned and its associated gamma-rays are summarized in Table 2.

It is clear that the tendency of the degree of the suppression of full-energy peaks in the Compton suppression mode that is represented by \( \frac{E_{bk,b}}{E_{bk,c}} \) is the reflection of the gamma-ray energies related to the detection efficiency of the BGO detector system and abundance for each nuclide listed in Table 2.

Dependence of full-energy peak efficiency of the 661 keV gamma-rays from 137Cs is shown in Fig. 10. In the figure error bars are fixed at the average value of 6.4%, which ranges actually from 5.3% at 0.674 g/cm² to 9% at 1.7 g/cm².

In this work the efficiency of 0.020X±5% at 1 g/cm² is employed to evaluate the minimum acceptable activity of 137Cs.

### 3 Peak-to-total Ratio

Peak-to-total ratio of the Ge detector has been measured with a set of point sources Prepared by Amersham, 68 Hg, 55Mn, 131Cs, 46Na and 56Co.

Typical source distance in the measurement is 5cm on the axis of the Ge crystal.

A simple method of extrapolation or interpolation has been used for stripping the peaks generated by K-X-rays, annihilation radiation as well, as the associated Compton continuum.

The result, of Peak-to-total ratio is shown as a function of gamma-ray energy in Fig. II in which statistical standard deviation is 0.5% at the maximum.

The result of fig. II shows that peak-to-total ratio of 661 keV gamma-rays and 835 keV gamma-rays, both from single gamma-ray emitter, is 0.281±0.2% and 0.250±0.1%, respectively.

### 4 Peak-to-Compton Ratio

The peak-to-Compton ratio is defined as the ratio of the counts/channel in the highest full-energy peak to the counts/channel in a typical channel of the Compton continuum associated with the full-energy peak.

The averaged counts/channel of the energy region of the Compton continuum ranging from 358 keV to 382 keV for the 661 keV gamma-rays from 137Cs and of the region 1040 keV to 10% for the 1332 keV gamma-rays from 60Co has been used, respectively.

The energy region for 137Cs and 60Co is shown in Fig. 6B and 7B, respectively.

The peak-to-Compton ratios for the gamma-rays of 661 keV (137Cs) and 1332 keV (60Co) have been calculated from the results of Fig. 6A and 7A.

The results with the single and the Compton suppression mode are presented in Table 5.

### 5 Compton Suppression Factor

The Compton suppression factor of the Ge-BGO gamma-ray spectrometer has been determined from the results of Figs. 12 and 17A.

The Compton suppression factor is defined as counts/channel of the single mode divided by counts/channel of the Compton suppression mode.

The results are shown in Figs. 12 and 13, in which the method of moving averages of six data points has been applied, and the factor in the region of full-energy peaks has been omitted.

Figure 12 shows that the Compton suppression factor at the Compton edge of the 661 keV gamma-rays from 137Cs is 10±1 and the factor averaged over the energy...
region used for determining Compton counts for the peak-to-total ratio is 0.2 on the average.

Scattering angle and the corresponding energy of scattered gamma-rays in the Ge detector have been inserted in Fig. 12.

Figure 13 shows that the suppression factor at the Compton edge of the 1332 keV gamma-rays from \( ^{60}Co \) and the factor in the energy region for the average Compton counts is almost the same value of 1.1. The factor at the Compton edge of the 117 keV gamma-rays is the maximum value of 10.7.

Behavior on Compton suppression factor of the Ge-BGO spectrometer can be summarized as the followings:

1. Appreciably large value of the Compton suppression factor around Compton edge proves that the plug and main BGO detectors work effectively for back-scattered gamma-rays from the Ge detector. Compton suppression factor around Compton edge in Fig. 12 proves that the detection efficiency of the BGO detector system for scattered gamma-rays of energy around 200 keV is more than 1/2\( ^0Co \).

2. The suppression factor at around 1-\( ^{12}C \) back scattered gamma-rays from the plug BGO detector is smaller compared to other region. This depletion of the factor is seemed to be caused by the back scattered gamma-rays by housing material of the BGO detector, which can not be detected by the plug BGO detector.

3. The suppression factor of a little more than four at a smaller scattered angle proves that the back-catcher BGO detector seems to be quite effective. This fact becomes more clearly in Fig. 13 obtained with \( ^{60}Co \). In this figure the energies of scattered gamma-rays from \( ^{60}Co \) become higher than that from \( ^{137}Cs \).

4. It is noticeable in Fig. 12 and 13 that the suppression factor of the region between the full-energy peak and the Compton edge that are resulted mainly in coincidence sum effect have also been suppressed rather effectively. This fact suggests that the BGO detector system has an appreciable detection efficiency for multiple-scattered gamma-rays. The suppression factor in the pulse height region decreases with increasing the pulse height. Because of that the energy of multiple-scattered gamma-rays decreases with increasing the pulse height of coincidence-sum events. In other words, the suppression factor in the region of pulse height decreases with increasing the pulse height of coincidence-sum events, since the shielding effect by detector housing against multiple-scattered gamma-rays increases with increasing the pulse height of coincidence-sum events.

3. Natural Background Level of the Ge-BGO Compton Suppression Gamma-ray Spectrometer

Natural background level of the gamma-ray spectrometer has been measured with the single and the Compton suppression mode, and the results are shown in Fig. 14.

The pulse height distribution with the single mode in Fig. 14 is multiplied by 100 for distinguishing both spectra easily.

Peak area of the main peaks observed in Fig. 14 is listed in Table (1). The result of Table (1) can be summarized as follow:

- In spite of full-energy peaks formed by cascaded gamma-rays such as \( ^{14}Pb \) and \( ^{14}Bi \), the suppression of peak area is not appreciable, because of that the solid angle of naturally occurring radionuclides subtended by the Ge detector is very small.
- Contrary to the above, the full-energy peaks of 207MPb are strongly suppressed with Compton suppression mode, because of that 207MPb is contaminant of the BGO crystal and the total detection efficiency of the BGO detector system is very high. The ratio of the peak area of the single mode to the Compton suppression mode, 1/S indicates that the peak area of the 104(1.4) keV is reduced to 0.0004 by 1/10 of the total detection efficiency of the BGO detector.
system for the main associated gamma-rays of 569.7 keV.

- The ratio of peak area of the doublet of the 511 keV, 7.86 is considerably larger compared to 1.77 of the 261 keV gamma-rays from $^{207}$TI. This result, shows that the peak area of 511 keV with the single mode is formed mostly by annihilation radiation generated in or near the BGO detector. The 511 keV peak and the single/ double escape peaks corresponding to 2614 keV from $^{211}$TI have not been observed at all by the measurement with 222Th source in the Compton suppression mode as shown in Fig. 8. Because of that the detection efficiency of the BGO detector system surrounding the Ge detector with almost 4n is very high (>95%) for annihilation radiation.

Compton suppression factor for natural background obtained from the result of Fig. 14 is shown in Fig. 15, in which the method of moving averages of six data points has been applied and no interpolation in f1111-energy peaks has been applied for estimating the suppression factor.

The Compton suppression factor shown in Fig. 15 is divided into two groups bordering the energy of the 1400 keV from $^{137}$Cs. In the lower pulse height group, the maximum and the minimum suppression factor is expected to be about 7 at around 1250 keV (830 channel) and about 3 at around 250 keV (250 channel), respectively.

In the higher pulse height group, the maximum and the minimum is about 10 at around 1500 keV (2650 channel) and about 4 at around 1460 keV (2111 channel), respectively.

Background levels of the energy region of the 661 keV from $^{137}$Cs have been obtained from the results of Fig. 14 as 7.83-$\sigma$ [1] (cps/keV)$\pm$3.4%. in the single mode and 1.31-$\sigma$ [1] (cps/keV)$\pm$8.4% in the Compton suppression mode, resulting in the suppression factor of 0.26 ($\pm$1%).

- I. Evaluation of the Minimum Acceptable Radioactivity of $^{137}$Cs

In the measurement of very weak radioactive samples like environmental samples, it is principal to grasp minimum acceptable radioactivity of spectrometers.

If minimum acceptable radioactivity of spectrometers is known in terms of main parameters characterizing spectrometers (energy resolution and detection efficiency, etc.) and in terms of measurement conditions (measurement time, background level and an acceptable statistical accuracy, etc.), it is very useful to design experiments and to improve the quality of measurement results.

In this work minimum acceptable radioactivity of $^{137}$Cs, AM has been evaluated by the method proposed by G. Y. Walford et al and J. A. Cooper.

The evaluation method expresses the AM as the following relationship:

$$ AM = \frac{1}{\sqrt{2 \cdot \frac{t}{E} \cdot P_{r} \cdot r \cdot n_{b} \cdot 4C_{h} R(E) \cdot n_{i}} - 1 + 8C_{h} R(E) \cdot n_{b} + 4C_{h} R(E) \cdot n_{i}} $$

where the $\sigma$: the acceptable coefficient of variation, which defines the precision of peak area:

$s \cdot \text{tan Jard deviation} \cdot (\frac{\text{net peak area}}{\text{net peak area}})$

the $\frac{t}{E}$: full-energy peak efficiency at a gamma-ray energy $E$ [keV],
the $P_{r}$ gamma-ray emission provability (abundance) [y/decay],
the $n_{b}$: measurement time [second],
the $R(E)$: energy resolution, FWHM [keV],
the $n_{i}$: average background counting-rate of the region of interest (ROI) in pulse height distribution [counts/keV] $\cdot \sigma$, the $n_{i}$: additional counting rate averaged over ROI, which is accompanied with the
evaluation of background in ROI [counts/keV].

The minimum acceptable radioactivity of $^{131}I$ Cs, $I_M$, has been done by the above relationship as a function of relative error, $\epsilon$, and measurement time, $T$ taken background level, $h$, into account.

In the evaluation the following instrumental and additional parameters have been used.

FWHM (Mil keV): 1.51 keV

Full-energy peak efficiency: 0.0208

Gamma-ray emission probability of the $^{131}I$ Cs: 0.61 keV gamma-rays from $^{133}Cs$.

Background counting-rate of the ROI: $7.88 \times 10^{-1}$ (counts/keV) in single mode. $1.21 \times 10^{-4}$ (counts/keV) in Compton suppression mode.

$h$: the constant to define the width of the ROI.

In usual low activity measurements, especially in many cases of the measurement of environmental sample. additional natural radioactivity, associated with the sample is more or less, introduced inside the detector shield, so that the sensitivity is decreased.

Table 7 presents background counting-rates at the energy region of the 661 KeV gamma-rays from $^{131}I$ Cs. $I_M$ has been measured with typical environmental samples. together with the result, of Fig. 14 without any sample. The result, of Table 7 is obtained with measurement time of 200 k to 80k seconds. depending on the sample.

Table 7 shows that the background level of the non-sample and the sea plant is comparable. and also the soil sample and the lake sediment is comparable. Therefore. the calculations of the minimum acceptable radioactivity of $^{131}I$ Cs based on the background levels of non-sample and the soil sample, have been made as a function of the coefficient, $h$, of variation. In the calculations, measurement time of $8$ hours and $18$X, of background counting-rate as the $h$, have been used.

The results of the above calculations are shown in Fig. 16.

When the maximum acceptable error is assumed to be 10%, the minimum acceptable activity of the Ge-BGO Compton suppression gamma-ray spectrometer for $^{131}I$ Cs are resulted in the activity, listed in Table 8.

Regarding the result, of Table 8. it is preferable to take the acceptable coefficient of variation (relative error) less than 0.3 (30%). It is widely recognized that the existence of the peak having an error more than 30% peak area is uncertain.

The minimum acceptable activity of $^{131}I$ Cs has been calculated as a function of measurement time under the same conditions as Fig. 16. The results calculated with the coefficient of variation of 0.1 and 0.3 are shown in Fig. 17 and Fig. 18, respectively.

The result of Table 8 clarify that the Ge-BGO Compton suppression gamma-ray spectrometer improves the sensitivity of detection of $^{131}I$ Cs activity about twice compared to the single spectrometer. The additional background introduced by the soil sample makes poor the sensitivity about 1.5 times compared to the sensitivity without the soil sample.

The minimum acceptable activities shown in Figs. 17 and 18 are summarized in Table 9, in which measurement times of 8 hours, one day and 2 days are combined with each coefficient of variation, 0.1 and 0.3.

**Conclusion**

A HP Ge Compton suppression gamma-ray spectrometer has been constructed with a BGO scintillation detector system as a Compton shield detector.

Energy resolution (FWHM) of the HP Ge and 25 em relative full-energy peak efficiency is $1.97$ keV and $76\%$ for the $1332$ keV gamma-rays from $^{137}Cs$, respectively.

The BGO detector system consists of three detectors, main (annulus type, 183.2 mm diam., $2(0)$ nun, annulus diameter: 83.2
plug (cylindrical 7(2) IIull diam ~7(2)2 nun and back-catcher (annulus type, X(1)-1 nun diam x 0.50 nun. annulus diameter: 2X-1mJ1)).

Energy resolution (FWHM) and peak-to-total ratio of the BGO detector system is 19%, and 0X5%, for the 001 keV gamma-rays from IrCs.

Total detection efficiency of the BGO detector system for the 1173 keV gamma-rays from 111Co and scattered gamma-rays of the Lr12 keV in Ge crystal is 8X% in total.

Peak-to-Compton ratio of the Ge-BGO Compton suppression gamma-ray spectrometer has been improved from 12R to 7X() with the Compton suppression spectroscopy in the case of the 061 keV gamma-rays.

Natural background level at the full-energy peak region of the 001 keV gamma-rays has been lowered from 7.9-100 cps/keV to 1.2x101 cps/keV with the Compton suppression spectroscopy.

With the Compton suppression spectroscopy the minimum acceptable radioactivity of u-Cs radioactivity has been improved from 0.091 Bq to 0.044 Bq under the conditions of measurement time of 8 hours and the coefficient of variation of 30%.

Under the additional natural background introduced by 1X g of soil (2x 103 cps/keV ill the single spectroscopy), the I11111111Um acceptable radioactivity of IrCs has been improved from 1.4 Bq to 0.066 Bq under the same parameters as the above.

The ultimate minimum acceptable radioactivity of 111Cs can be actually concluded as 0.015 Bq that is obtained under the conditions of 30%X, or the coefficient of variation, measurement time of 2 days and non-additional background.

References
1. J. Mareschal and Herve Le-Gal, "Radioactivity Measurements of Be-O, Samples", private communication from Caismane (France)
5. A. Daourka, Nucl. Instrum. Meth., 21111377 (19R2)
Table 1 The result of the measurements of characteristics of the BGO detectors and the BGO detector system

<table>
<thead>
<tr>
<th></th>
<th>FWHM (661 keV: J:17Cs)</th>
<th>Peak-to-total Ratio (661 keV: 137Cs)</th>
<th>Source position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main BGO</td>
<td>18.3° ± 0.81</td>
<td>0.811 ± 0.16%</td>
<td>Center of annulus</td>
</tr>
<tr>
<td>PlugBGO</td>
<td>12.7° ± 0.64</td>
<td>0.647 ± 0.08%</td>
<td>15 cm from BGO</td>
</tr>
<tr>
<td>Back-catcher BGO</td>
<td>25.0° ± 0.46</td>
<td>0.461 ± 0.10%</td>
<td>5 cm above BGO</td>
</tr>
<tr>
<td>BGO detector system</td>
<td>19.9° ± 0.83</td>
<td>0.830 ± 0.10%</td>
<td>Center of annulus</td>
</tr>
<tr>
<td>BGO detector system</td>
<td>19.1° ± 0.84</td>
<td>0.848 ± 0.07%</td>
<td>3 cm from Ge, 2 cm from plug BGO</td>
</tr>
<tr>
<td>BGO detector system</td>
<td>10.6° ± 0.27 (2505 keV: sum of 60Co)</td>
<td>0.279 ± 0.09%</td>
<td>Center of annulus</td>
</tr>
<tr>
<td>BGO detector system</td>
<td>12.1° ± 0.27 (2505 keV: sum of 60Co)</td>
<td>0.273 ± 0.16%</td>
<td>3 cm from Ge, 2 cm from plug BGO</td>
</tr>
</tbody>
</table>

# 0.534 for 3 inch diam. x3 inch NaI(Tl) crystal (3)

Table 2 Energy resolution of the HP Ge gamma-ray spectrometer

<table>
<thead>
<tr>
<th></th>
<th>FWHM (keV)</th>
<th>FWTM (keV)</th>
<th>FWTM/FWHM*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1332 keV (60Co)</td>
<td>1.97</td>
<td>3.65</td>
<td>1.86</td>
</tr>
<tr>
<td>661 keV (1:17Cs)</td>
<td>1.51</td>
<td>2.79</td>
<td>1.85</td>
</tr>
</tbody>
</table>

*: the theoretical value: 1.83

Table 3 Full-energy peak efficiency of the HP Ge detector for volume source (Sample: 75 mm diam. x34±1 mm, SD: 3 mm)

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Energy (keV)</th>
<th>Efficiency in Single Mode, %</th>
<th>Efficiency in Compt. Sup. Mode, %</th>
<th>( eslec )</th>
<th>Density (g/cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:17Cs</td>
<td>661</td>
<td>0.0208±2.5%</td>
<td>0.0208±2.5%</td>
<td>1.00</td>
<td>0.674</td>
</tr>
<tr>
<td>1:1~Cs</td>
<td>795</td>
<td>0.0158±3.8%</td>
<td>0.0007±3.5%</td>
<td>21.7</td>
<td>0.674</td>
</tr>
<tr>
<td>ti(^{60})Co</td>
<td>1332</td>
<td>0.0129±5.4%</td>
<td>0.0016±5.4%</td>
<td>8.01</td>
<td>0.347</td>
</tr>
<tr>
<td>( ^{60}Zn )</td>
<td>1461</td>
<td>0.0113±4.2%</td>
<td>0.0113±4.2%</td>
<td>1.00</td>
<td>0.674</td>
</tr>
<tr>
<td>2(^{137})TI</td>
<td>2614</td>
<td>0.0061±4.0%</td>
<td>0.000326±3.6%</td>
<td>18.8</td>
<td>1.50</td>
</tr>
</tbody>
</table>
Table 1: Energies and abundances of the gamma-ray's and the associated gamma-rays.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Energy (eV)</th>
<th>Abundance (%)</th>
<th>Gamma-rays associated</th>
<th>Energy (keV)</th>
<th>Abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-127CS</td>
<td>77.11</td>
<td>HGA</td>
<td>G18</td>
<td>4.94</td>
<td>t04</td>
</tr>
<tr>
<td>99mTc</td>
<td>133~</td>
<td>100</td>
<td>117.3</td>
<td>88.4</td>
<td>118.4</td>
</tr>
<tr>
<td>203Tl</td>
<td>2614</td>
<td>D.8</td>
<td>277</td>
<td>6.8</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>580</td>
<td>86.0</td>
<td>860</td>
</tr>
</tbody>
</table>

Table 5: Peak-to-Compton ratio for 661 keV (I-127CS) and 1332 keV (99mTc) Gamma-rays.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Nuclide</th>
<th>Mode</th>
<th>Peak-to-Compton Ratio</th>
<th>Channel Width (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(187)I</td>
<td>I-127CS</td>
<td>Single</td>
<td>78</td>
<td>O.20G</td>
</tr>
<tr>
<td>(~201)I</td>
<td>99mTc</td>
<td>Compton Sup.</td>
<td>50</td>
<td>O.HH</td>
</tr>
<tr>
<td>(135)-1</td>
<td>203Tl</td>
<td>Single</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Peak area ratio of main peaks in natural background spectra with single and Compton suppression mode.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Nuclide</th>
<th>Peak Area (cm^2)</th>
<th>Ratio of Single/C. Sup.</th>
</tr>
</thead>
<tbody>
<tr>
<td>18G**</td>
<td>287HAt2H2U</td>
<td>0.00078±2.5%</td>
<td>0.00805±4.2%</td>
</tr>
<tr>
<td>218.7Co**</td>
<td>211Pb</td>
<td>0.0122±2.1%</td>
<td>0.0128±1.1%</td>
</tr>
<tr>
<td>211Pb</td>
<td>214Pb</td>
<td>0.0047±2.3%</td>
<td>0.0045±1.1%</td>
</tr>
<tr>
<td>511** Annihilation</td>
<td>0.0101±2.1%</td>
<td>0.0099±1.4%</td>
<td>1.0±1.2%</td>
</tr>
<tr>
<td>FI2O7</td>
<td>217.8Pb</td>
<td>0.0007±1.0%</td>
<td>0.0008±1.0%</td>
</tr>
<tr>
<td>181.2Bi</td>
<td>211Bi</td>
<td>0.0004±1.0%</td>
<td>0.0005±1.0%</td>
</tr>
<tr>
<td>111.3 In</td>
<td>220W</td>
<td>0.00127±1.7%</td>
<td>0.00127±1.7%</td>
</tr>
<tr>
<td>106.5Mo</td>
<td>211Mo</td>
<td>0.00012±1.8%</td>
<td>0.00012±1.8%</td>
</tr>
</tbody>
</table>

Note: = Hat io of peak area of single mode to Compton suppression mode.
3. Doublet (or interfered by the neighboring peak.)
Table 7 Background counting-rate at the full-energy peak region of the 661 keV gamma-rays from $^{137}$Cs measured with the Ge-BGO gamma-ray spectrometer

<table>
<thead>
<tr>
<th>Sample</th>
<th>Background Counting-rate (cps/keV)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Mode</td>
<td>Compt. Sup. Mode</td>
</tr>
<tr>
<td>None</td>
<td>$7.58 \times 10^4 \pm 8.0%$</td>
<td>$1.23 \times 10^{-4} \pm 2.0%$</td>
</tr>
<tr>
<td>Soil</td>
<td>$1.99 \times 10^4 \pm 5.0%$</td>
<td>$3.0(\times 10^{-5} \pm 12%$</td>
</tr>
<tr>
<td>Seaplant</td>
<td>$8.0 \times 10^{-4} \pm 100%$</td>
<td>$1.48 \times 10^{-4} \pm 29%$</td>
</tr>
<tr>
<td>Lake Sediment</td>
<td>$1.6 \times 10^{-4} \pm 9.3%$</td>
<td>$2.19 \times 10^{-4} \pm 24%$</td>
</tr>
</tbody>
</table>

Table 8 Minimum acceptable radioactivity for $^{137}$Cs of the Ge-BGO Compton suppression gamma-ray spectrometer (Relative error: 30%. Measurement Time: 8 hours)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Single Mode</th>
<th>Compton Suppression Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0.091 Bq</td>
<td>0.044 Bq</td>
</tr>
<tr>
<td>Soil</td>
<td>0.14 Bq</td>
<td>0.006 Bq</td>
</tr>
</tbody>
</table>

Table 9 Minimum acceptable radioactivity for $^{137}$Cs of the Ge-BGO Compton suppression gamma-ray spectrometer with measurement time and the coefficient of variation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Measurement Time</th>
<th>Single Mode</th>
<th>Compton Suppression Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coefficient of Variation</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>None</td>
<td>8 hours</td>
<td>0.35</td>
<td>0.091</td>
</tr>
<tr>
<td></td>
<td>1 day</td>
<td>0.17</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>2 days</td>
<td>0.11</td>
<td>(1.021)</td>
</tr>
<tr>
<td>Soil</td>
<td>8 hours</td>
<td>O.25</td>
<td>0.077'</td>
</tr>
<tr>
<td></td>
<td>1 day</td>
<td>0.17</td>
<td>0.053</td>
</tr>
</tbody>
</table>
Fig. 9. Possible X-ray Disintegrations of Uranium-238.

Fig. 10. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 11. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 12. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 13. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 14. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 15. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 16. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 17. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 18. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 19. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 20. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 21. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 22. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 23. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 24. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 25. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 26. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 27. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 28. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 29. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 30. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 31. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 32. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 33. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 34. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 35. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 36. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 37. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 38. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 39. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 40. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 41. X-ray Spectrum of Uranium-238 with and without Suppression.

Fig. 42. X-ray Spectrum of Uranium-238 with and without Suppression.
**Figure 1** Pulse height distribution of Natural Barry and with and without Zoysia grass. Gamma-ray spectrometer.
Coeficient of Variation: 0.3

Fig. 1: Maximum Acceptable Level of Voltage Deviation vs. Time, group 1

Measurement: Time (hours)

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