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*

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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 30% and measurement time of 8 hours.

Abstrak. Construction of a Ge-BGO Compton Suppression Gamma-ray Spectrometer and Its Application to Envirnnmental Samples, Part 1: Thc System of the Spectrometer and Its Basic Performance, Untuk mengembangkan spcktrometer sinar-x Ge dengan kepekaan yang sangat tinggi, telah dibuat sebuah sistem spektromcter sinar-x penindas Compton dengan menggunakan detektor pelindung BGO. Sistem detektor BGO mendetcksi 88% sinar gamma dari ^{60}Co yang digunakan dalam prinsip sistem penindas. *Peak-to-Compton ratio* untuk sinar gamma berenergi 661 keV dari ^{137}Cs telah diperbaiki dari 128 menjadi 786 dengan spektroskopi penindas Compton. Melalui pengembangan spektrometer ini radioaktivitas ^{137}Cs minimum yang dapat diterima meningkat dari 0.091 Bq menjadi 0.044 Bq dengan koefisien variasi 30% dan waktu pengukuran 8 jam.

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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 the one of the useful techniques to maintain natural environment.. and to assure safe normal operation of nuclear facilities.

High sensitive gamma-ray spectrometers have being 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 analized 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 radioactivitv, . especially in low level counting.

Suppression of Compton continuum will be the most efJective method to reduce the background in thc 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 ı r Cs in natural environment, and for the leachability test of ı r Cs in radwaste management fac·ilities. a Compton suppression Gc gamma-ray spectrometer has been constructed. A BGO (Bismuth Gennanatc of the composition Bi,Gc10d scintillation detector system has been used as a Compton suppression detector.

Due to the high atomic number (Bi: IB) and high density (7.13 g/cnr'). 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 systcm achieves an appreciable suppression of Compton background. i. e. makes possible to detect further lower level of radioactivity of 1;-Cs compared with the achievable level by the usual (single) mode of this spectrometer.

1. Configuration of the Ge-BGO Compton Suppression Gamma-ray 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 tile Ge detector have been rejected at a linear gate circuit in anti-coincidence mode by the signals. which are generated in tile Ge detector and tile BGO detector system at tile 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-Tee. Inc. (USA)

Model: . IGC 40195. SeT. No.: 2631

Detector Geometry: p-type Coaxial

Crystal Size: ()3 nun in diam ., 59 nun in length

Active Volume: 176 cnr'

Dead layer: I nun

Detector/Window Distance: 5 111111

Relative Efficiency: 4().I'X,

FWHM: UQ keY at 1332 keV ("Co). X60 eVat 122 keV (5-CO)

1.1.'2 *HGD Detector System*

For synthesizing low-background EGO crystals. bismuth compound (Bi~03) of the lowest radioactive contamination has been chosen'!', especially avoiding the contamination of ~1I"\1Bithat is tile one of fallout-nuclides'?' caused by nuclear testing. The radioactive concentration of ~f17MBiin the Bic03 used for the crystals is less than

0.03 Bq/kg.

The background count-rate of the BGO detector system resulting from the contamination is less than 2 counts per second. which is less than I'X. 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 Gc detector. . into which the Gc detector is inserted.

Manufacturer: Crismatec (France)
Model: EES-Model V
Crystal Shape: Annulus
Crystal Size: External Diam.: Un.2 nun.
Internal Diam.: 83.2 nun
Length: 200 nun.
Crystal Thickness: 50 mm
A1UlUIus Diameter: 80.2 nun
Crystal Weight: . 29.78 kg
Housing Thickness: I. 5 nun aluminum alloy
FW'HM: Better than 20'Yo(GGI keY:. !:liCS)
Notes: Seven optically independent side clement 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 Ole main BGO detector in usual uses.

Manufacturer: Crismatec (France)
Model: . EEP-Model V
Crystal Shape: Solid Cylinder
Crystal Size: 70.2 mm diam. x 76.2 nun
Crystal Weight: . 2A5 kg
Housing Thickness: 0.8 nun aluminum
FWHM: Better than 13% (o(d keY:. DiCs)
Notes: One photomultiplier of 3 inch diameter

(c) Back-catcher BGO Detector

Manufacturer: Crismatec (France)
Model: EEC -Model V
Crystal Shape: Annulus separated into Ist half and 2nd half for surrounding the dip-stick of the Ge detector
Crystal Size: External Diam.: X(U 1111l1.
Internal Diam.: 28.4 111m,
Length: 50 mm.
Crystal Thickness: 26 nun
Annulus Diameter: 25.4 nun
Crystal Weight: . 1.32 kg
Housing Thickness: 0.8 nun aluminum
FWHM: Better than 25'% (661 keY:. 137CS)

Notes: The annulus consists of two independent BGO detectors: the half detector consists of two BGO segments. and each segment is equipped with one photomultiplier of one-inch diameter.

1.1.3 Shielding ofthe Ge-BGO Detector System

The Ge-BGO detector system is shielded by low-background lead in thickness of 10 em.

The inside of the lead shield is lined with low-background oxygen-free copper in thickness of 5 mm and Lucite in thickness of2 nun.

1.2 Arrangement of the Electronic Units

Block diagram of Ole 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 O.5Us and 50s. respecti vel y.

Shaping time constant of 50s has been set for Ole spectroscopy amplifier of HP Ge detector.

l.Z:. i Linear/Logic Pulse System of the lll? Ge Detector

Preamplifier: PGT RG llB/C
Spectroscopy Amplifier: Canberra 1413
Linear Delay: ORTEC 427 A
Pulse Height Adjuster (No. I Input of SUIll Amplifier): Canberra 1465A
Timing Single Channel Analyzer: ORTEC 551

1.2.2 Linear Logic Pulse Svsteni or the BUO Detector Sysiem

Sum for Each BGO: Three Channel Preamplifier/Line Drivers. Cyberstar (France) EES-VIEEC-V

Sum Amplifier: Three Channel Sum-Shaping-Base Line Restorer Amplifier (Gaussian I us fixed peaking time). Cybcrstar CSY-lSA

Timing Single Channel Analyzer: ORTEC 455

Gate/Delay Generator: ORTEC 41 6A

1.2.3 Logic Systetn for HP Ge and EGO Systems

Anti-Coincidence: ORTEC -l14A

Gate/Delay: ORTEC -l1()A

Linear Gate/Stretcher : ORTEC 542

I.} .J Xlultichannel Analvzer and Data Processor

Multichannel Analvzer: Seiko EG&G 7X()() with two Analog-to-Digital Converters (Sciko I X20)

Data Processor and Output Machines: NEC PC YX()I YX with a Software/Data Base by Sciko. Plotter (Roland) and Line Printer (NEC)

2. Measurements of Basic Characteristics of the Gc-BGO Compton Suppression Gamma-ray Spectrometer

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

Minimum acceptable radioactivities of the Ge-BGO Compton suppression gamma-ray spectrometer has been evaluated for Lr Cs in terms or the coefficient or variation and measurement time. The change of background level into is taken into account

2.1 Performance of the BGO Detector System

Pulse height distribution of the main. plug and back-catcher BGO detectors have been measured with use of a point source of Ir. Cs. In the measurements. the output amplitude of each detector has been adjusted to give almost the same pulse height by controlling high voltage power supply. which is equipped with each detector.

The pulse high distributions of 137 Cs of the main. plug and back-catcher BGO detectors are shown in Fig. 3.

The pulse height distributions of the BGO detector system have been measured by uSH1g point sources of ι>lCs and 6"Co as shown in Figs. 4 and 5. and the results of FWHM and peak-to-totai ratio are tabled 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, x3 inch BGO detector is 1.21 times or that of the same size Nal(TI) 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 Gc Detector

The certified values of the HP Ge detector by the manufacturer. UQ kcV of FWHM and 46.1 'X, 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 ill Fig. 2 have been done.

In the measurements. points sources of

13- CS. ""CO and mixed nuclides of ("'Co. I.r Cs and c~xTh have been used in both spectroscopy modes of the single (normal) and Compton suppression. The results of the measurements are shown in Figs. (iA. 7A and X. It is apparent that the pulse height distributions of Figs. (iA and 7A arc 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 "'Co as well as the effective reduction of Compton continuum.

2.2.1 Energv Resolution

Measurements of cncrgj resolution of the HP Gc detector for 1332 keV ("Co) and ()(,I keY (r 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 FWTMlFWHM.

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

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

The ratios. FWTMlFWHM 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 I~n (HWTMfHWHM = ·Ul)a/2.35cr. where σ is standard deviation).

2.2.2 Detection Efficiency

The 25 em relative efficiency of the HP Ge has been tested. and no appreciable change. i.e. more than I 'X, in the efficiency has been observed.

Intending to obtain full-energy peak efficiency for volume samples. three volume sources containing I};Cs. IJ.1CS. r,,C() . 1"K and/or ~oxTI have been prepared with use of induced and natural radioactivity.

Density of the sample ranges widely from ().347 g/cur' to 1.50 g/cnr, 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 tile 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 arc 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'X• .which are three standard deviations of 1.14CS.

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 (~:s) to the one in tile Compton suppression mode (Eel. f.slEc is listed.

The ratio for single gamma-ray from Ir Cs and 4"K is unity in both mode. i.e. any change in tile efficiency has not been observed.

Contrary to single gamma-ray emitters. the ratios for the gamma-ray emitted from multiple gamma-ray emitters. IJ4CS. "'Co and ~(~Tl, 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 tile stun of the total detection efficiency of the BGO detector system for the associated gamma-ray s 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. BUI' can be calculated as 95.--l'X. for 134CS, 87.5'1., for wCo and 9--l.7% for ~'Il<TIfrom the following relationship '4':

$$\varepsilon_{BGO} = 1 - (\varepsilon_S / \varepsilon_C)^{-1}$$

Energy and its abundance of gamma-my concerned and its associated gamma-rays arc summarized in Table --l.

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 !:s lt;,' 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 --l.

Dependence of full-energy peak efficiency of the (,61 keY gamma-rays from 13;CS is shown in Fig. 10. In the figure error bars arc fixed at the average value of 6.<i%. which ranges actuallx from 5.3% at 0.674 g/cnr' to 9% at 1.7X g/cm'.

In this work the cfficicncx of O.020X±5% at I g/cnr' is employed to evaluate the minimum acceptable activity of 1FCS.

::.::.3 Peak-to-total Ratio

Peak-to-total ratio of the Gc detector has been measured with a set of point sources P!epared by Amcrsham, :'' Hg. ''Mn. i\3 Cs. --Na and ''''Co.

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-.\-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 kcV-gamma-rays, both from single gamma-ray emitter. is O.281±O.2% and O.250±O.1 %, respectively.

2.2. -I 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 Ole energy region of the Compton continuum ranging from 358 keY to 382 keY for the 661 keY gamma-rays from a'.,- Cs and of the region 1040 keY to 10% for the 1332 keY gamma-rays from wCo has been used, respectively (:ii.

The energy region for JJ7CS and nl)Co is shown in Fig. 6B and 7B. respectively.

The peak-to-Compton ratios for the gamma-rays of 661 keY (^{137}CS) and 1332 keY (''Co) 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.

2.].5 Cumpton Suppression Factor

The Compton suppression factor of the Ge-BGO gamma-ray spectrometer has been determined from the results of Figs. (,A and 7A.

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 ()61 keY gamma-rays from J:l7Cs is IO.--l and the factor averaged over the energy region used for determining Compton counts for the peak-to-total ratio is ().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 keY gamma-rays from 6<'Co and the factor in the energy region for the average Compton counts is almost the same value of l).-l. The factor at the Compton edge of the II n keY ganuna-rays is the maximum value of 10.7.

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

- 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 keY is more than l)0'Y",
- The suppression factor at around I~Wo 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 b~ housing material of the BGO detector., which can not be detected by the plug BGO detector..
- 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 (,"Co. In this figure the energies of scattered gamma-rays from 6<'Co become higher than that from u-Cs.
- 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 multi pie-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 ganuna-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. l-l is listed in Table ().

The result of Table () can be summarized as follow:

- In spite of full-energy peaks formed by cascaded gamma-rays such as c14Pb and cl4Bi. 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 20iMPb 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. I().S indicates that the peak area of the IO().H> keY is reduced to ()U;:; by l)-IX, of the total detection efficiency of the BGO detector

system for the main associated gamma-rays of 569.7 keY.

- The ratio of peak area of the doublet of the 51] keY. 7.86 is considerably larger compared to I.77 of the 261 .U ke V gamma-rays from 2"TI. This result. shows that the peak area of 511 keY with the single mode is formed mostly by annihilation radiation generated in/or near the BGO detector. The 511 ke V peak and the single/ double escape peaks corresponding to the 2614 ke V from 211xTI have not been observed at all by the measurement with 22xTh 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 (>9S'%) 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 cncrgv of the 14()() keV from 'IIK.

In the lower pulse height group. the maximum and the minimum suppression factor is expected to be about 7 at around 1250 keY (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 I SOO kc V (2650 channel) and about 4 at around 146() ke V (2 II () channel). respectivel y.

Background levels of the energy region of the 661 keY from I:r Cs have been obtained from the results of Fig. 14 as 7.83.<]().I (cps/keV)±3.4'X, in the single mode and 1.31 x 1ư' cps/keV±8.4% in the Compton suppression mode. resulting ın the suppression factor of ().O±6.'.1%).

-I. Evaluation of the Minimum Acceptable Radioactivity ofB7 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 nunnnum acceptable radioactivity. of I3'CS., AM has been evaluated by the method proposed by G. Y. Walford et al (6) and 1. A. Cooper m.

The evaluation method expresses the .1\I as the following relationship:

$$A_{11} = \frac{1}{2C^2 \varepsilon(E) P_r t}\left(1 + \sqrt{1 + 8C^2 h R(E)\,\overline{n_B}\,t + 4C^2 h R(E)\,\overline{n_J}\,t}\right)$$

where the (': the acceptable coefficient of variation. which defines the precision of peak area:

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

the ~;(E): full-energy peak efficiency at a ganuua-ray energy E [kcV].

the Pr gamma-ray emission provability (abundance) [y/decay].

the t: measurement time [second].

the R(E): energy resolution. FWHM [keV].

the $\overline{n_B}$: average background counting-rate of the region of interest (ROl) in pulse height distribution [counts/kev] '.

the $\overline{n_J}$: additional counting rate averaged over ROI. which is accompanied with the

evaluation of background in ROI [counts/kev].
the h: the factor which when multiplied by the energy resolution R(i:j IFWHM I. gives the region (width) of the ROI

The minimum acceptable radioactivity of I:r Cs, .lM has been done by the above relationship as a function of relative error. (' and measurement time. I taken background level., 11B into account. .

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

FWHM (Mil keY): 1.51 keY

Full-energy peak efficiency: 0.0208 (volume source: 75 nun diam.x74 mm. source-distance: 1 mm)

Gamma-ray emission probability of the 061 kcY gamma-rays from 1J" Cs: (Ut, I

, Background counting-rate of the ROJ:. 7.88x 10"1(counts/kev)' in single mode.

I.21 x lO-4 (counts/kev)' in Compton suppression mode

the constant to define the width of the ROJ., h: 2

In usual low activity measurements. especially in many cases of the measurement of environmental sample. additional natural radioactivity associated with the samples 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 keY from 13;Cs 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 ır Cs based on the background levels of non-sample and the soil sample have been made as a function of the coefficient of variation. In the calculations. measurement time of X hours and IS'X, of background counting-rate as the IГ,. have been used.

The results of the above calculations arc shown in Fig.)(i.

When thc maximum acceptable error is assumed to be 10%. the minimum acceptable activity of the Ge-8GO Compton su~p!ession gamn_1a-ray spectrometer for ' Cs are resulted 111 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% 111peak area IS uncertain (6, (~I.

The minimum acceptable activity of 13i Cs has been calculated as a function of measurement time under the same conditions as Fig. Hi. The results calculated with the coefficient of variation of 0.1 and 0.1 are shown in Fig. I() and Fig. 17. respectively.

The result of Table 8 clarify that the Ge-8GO Compton suppression gamma-ray spectrometer improves the sensitivity of detection of 1:1"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 coeffic'ient 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 sh.ield detector.

Energy resolution (FWHM) of the HP Ge and 25 em relative full-energy peak efficiency is I.97 keY and ·Ud % for the 1332 ke Y gamma-rays from (,(ICo. respectively.

The BGO detector system consists of three detectors. main (annulus type. 183.2 mm diam.x2()() nun. annulus diameter: 83.2

nun). plug (cylindrical t~pc. 7(>2 IIUll diam ~7().2 mill and back-catcher (annulus type, X().-l nun diam. x50 nun. annulus diameter: 2X.-lmJ11).

Energy resolution (FWHM) and peak-to-total ratio of the BGO detector system is 19%, and OX5%, for the 00 I keV gamma-rays from IrCs.

Total detection efficiency of the BGO detector system for the 1173 ke V gamma-rays from !I'CO and scattered gamma-rays of the Lrl2 keY 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 ke V gamma-rays.

Natural background level at the full-energy peak region of the 00 I keY gamma-rays has been lowered from T.')» r0 cps/keV to 1.2x](r1 cps/keY with the Compton suppression spectroscopy.

With the Compton suppression spectroscopy the nunrnum 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 3()'%.

Under the additional natural background introduced by IX-l g of soil (2x 10'3 cps/keV ill the single spectroscopy). the 1I11I111llUm acceptable radioactivity of I:r Cs has been improved from ().1-l Bq to O.()66 Bq under the same parameters as the above.

The ultimate minimum acceptable radioactivitx of 11'. Cs can be actually concluded ,IS 0.015 Bq that is obtained under the conditions of 3()'X, or the coefficient of variation. measurement time of 2 days and non-additional background.

References

I. J. Mareschal and Herve Le-Gal. *"Radioactivitv Measurements ofBe-O Samples "*, private communication from Cnismatec (France)
2. A.Sh.inohara, T. Saito and H. Baba, *"Radioisotopic Impurities in Bismuth Chemicals ", Appl. Radiat. Isot.*, *37* (IO), 1025 (1980)
3. R. L. Heath, *"Scintillation Spectrometry: Gatntna-rav Spectrum Catalogue "*. IDO-166880-t, 2nd edition (19r>4)
4. T. Tojo and M. Kondo, *"/1 Pair and Escape-Suppressed Spectrometer Csing a Large NaIt'Il) Annulus and a Ge Detector for Xeutron Capture (jal111-rav Spectrometer "*. in Japanese, **JAERI-M** 7910 (197X)
5. A. Damkjaer, *Nucl. Instruni. Meth.* 21111377 (l9R2):
0. G. F. KnolL *"Radiation Detection and Measurement "*,2nd edition, p. 41 L John Wiley & Sons (1989)
7. G. V Walford and W. B. Gilboy, *'Fundamentals ofSensitivity Limits in Low Level Counting "*, **ERDA** Conf--72118115-P, 135 (1972)
R. 1. A. Cooper. *Nucl. Instr and Meth*. 82, 273 (197())
9. G. V Walford. *"The Characteristic.s and Loll' Level Counting Capabilitie.s l!f (ie(Li) Ganuna Rav Spectrometers "*, Ph.D. Thesis, University of Surrey, UK (1972)

Table 1 The result of the measurements of characteristics of the BGO detectors and the BGO detector system

	FWHM (661 keV: J:l7Cs)	Peak-to-total Ratio (661 keV: 137CS)	Source position
Main BGO	18.3°"	0.811±0.16'70	Center of annulus
PlugBGO	12.7""	0.647±0.08%#	15 em from BGO
Back-catcher BGO	25.0°"	0.461±0.100,"	5 ern above BGO
BGO detector system	1ɑ,9"	0.830±0.10""	Center of annulus
BGO detector' system	19.1 ""	0.848±0.07""	3 em from Ge, 2 em from plug BGO
BGO detector system	10.6°" (2505 keV: sumof =C,»)	0.279±0.09,}" (2505 keV: sum of60Co)	Center of annulus
BGO detector system	12.1"" (2505 keV: sum of (;0Co)	0.273±O.16"" (2505 keV: sum oPOCo)	3 ern from Ge, 2 cm from plug BGO

0.534 for 3 inch diam. x3 inch NaI(TI) crystal (3)

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

	FWHM (keV)	FWTM (keV)	*FWTM/FWHM**
1332 keV (60CO)	1,97	3.65	1,86
661 keV (1:17CS)	1,51	2.79	1,85

*: 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)

Nuclide	Energy (keV)	Efficiency in Single Mode, ES	Efficiency in Compt. Sup. Mode, eo	*eslec.*	Density (g/cm")
1:17CS	661	0.0208±2.5%	0.0208±2.5%	1,00	0.674
1:l~CS	795	0.0158±3.8%	0.00073±18%	21,7	0.674
ti°Co	1332	0.0129±5.4%	0.0016l±5.4%	8.01	0.347
~OK	1461	0.0113±4.2'10	0.0113±4.2%	1,00	0.674
2°~TI	2614	0.00614±1.0'%	0.000326±3.6%	18.8	1,50

Tablp 1 Enprgim; and abundances of the gamma-ray's concerned and thp associat ed gamma-rays

Nuclid«	(;amma-rar concornod		Gamrna-ravs associated	
	Energy (h\')	Abundance (%)	Energy (kPV)	.\bundancp (,X,)
I:;-ICS	7!l:)	HGA	Gti!l	I G.4
			ti04	!J7.fi
';'l(~O	1:l:3~	100	117:3	88.4
20;;'1'1	2614	D8.8	277	6.8
			510	21.6
			58:3	86.0
			860	12.0

Table 5 Peak-to-Compton ratio for 661 keV (l:i7CS) and 1:~:~2keV (';UCo) Gamma-rays

Energy (ke V)	Nuclide	Mode	Peak-to- Compton Ratio	Channel Width keV)
(-)(-)1	t:i7('s	Singl!~	128	O.20G
		Compt. Sup	78ti	
1:l:1~	''t''o	Single	5D	O:HH
		Compt Sup.	11(-)	

Tabl(~ (j Poak aWH or main paaks in natural background speer rum measuror] with single and Compton suppression mode

Energy (ke \')	Nuclide	Peak Area (ens)		Ratio of Single/C. Sup. *
		Sinzle	Comvton Sup.	
18G**	~2';Ha/2:i:'U -	o.007BR±G.2%	O.00805±4. 0%	O.D9±7.4%
2:18.(-j**	21-1Pb	OO122±4.::l%	O.0 1l9±:.3.0%	1.0:~±5.2%
:~51.9	214Pb	O.OO477±8.;)%	O.0044!:l±5.1 %	1.06±9.9%
511 **	AnnihipooTI	0.0 1G4±~.!l%	O.OOI9G±!_).O%	7.86±D.5%
FiG!J.7	2il7.\IPb	O.Ol:H±2.!J%	OOO]4D±D.G%	8.DH±]O.O%
fi8:l.]	2l°'1'1	O.OOfi47±fi.9%	O.OO~7:~±5.D%	2.00±8.:3%
fiOD.:1	21.1Bi	O.0048:)±(j :1%	o.OO:1n±4.8%	1:lO±7!)%
!l11. 1	220.\(,	0.00:127 ±7.7%	O.OO:lO(j±li.]%	1.07±D.2%
lO(;:U;	211\]1I>	O.Olll±~!)%,	O.OOOG±l 1.8%	l(i8±1i'il%
Lll:.m:l.	~I iii	o.00 1~± 18.0%	o.00 1~8±!J.~%,	0.!JD±~O.:3%
11(;0.H	'''1\	O.0484± 1.1%	O.04 'i'(i± l. 0%	1 02± 1.;'':>%,
~(; Jl4 li	2l10'lI	OOO:n 1±4.:1%	o.OO~1O±5.2%	1.77±G7%,

=: Hat io of peak area of singl« mode to Compton suppression morle
=. Doublet (or; interfered by t.he neighboring peak)

Table 7 Background counting-rate at the full-energy peak region of the 06 I keV gamma-rays from Ir Cs measured with the Ge-BGO gamma-ray spectrometer

Sample	Background Counting-rate (cps/keV)		Remarks
	Single Mode	Compt. Sup. Mode	
None	7.S8x ur' ±8.0%	1.23x 10-4±2.0%	
Soil	I. 99x 10-' ±5.0%	3.0(ix 10^{-4} ±12%	75 diam,×33 mm 184.2 g, 1.26 g/cm^3
Seaplant	8.0 I x 10^{-4} ± I00;.,	1.48x 10^{-4} ±29%	75 diam,×32 mm 91.34 g, 0.646 g/cm^3
Lake Sediment	l..a x Iu ±9.3 'X,	2.19x 10^{-4} ±24'Yo,	75 diam,×35 mm 275.4 g, 1.78 g/cm^3

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

Sample	Single Mode	Compton Suppression Mode
None	0.091 Bq	0.044 Bq
Soil	0.14 Bq	0.006 Bq

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

Sample	Measurement Time	Single Mode		Compton Suppression Mode	
		Coefficient of Variation		Coefficient of Variation	
		0. I	0.3	0.1	0.3
None	8 hours	0.35	0.091	0.23	(l.()44
	Idm	0.17	0.049	O.Ol)6	0.022
	2 days	0.11	(l.021	(l.()21	(l.015
Soil	8 hours	OA9	0.14	0.29	0.066
	I day	0.25	0.077'	o.n	0.035
	2 days	0.17	0.053	0.085	0.024

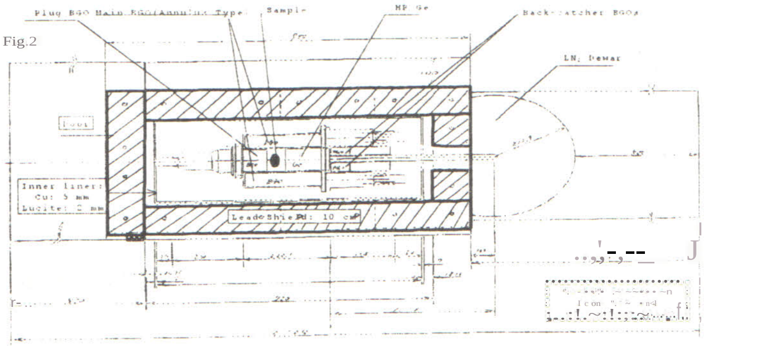


Fig. 1 [illegible]

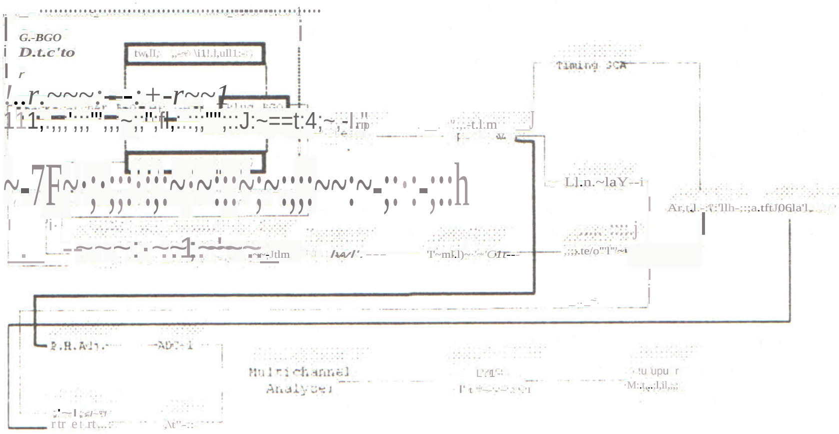


Fig. 2 [illegible]

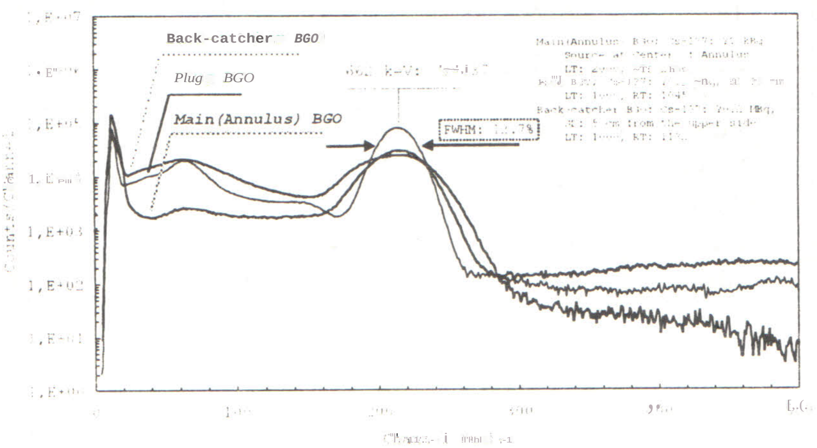


Fig. 3 Pulse Height Distributions of Cs-137 by the Main, Plug and Back-catcher BGO Compton Shield Detector

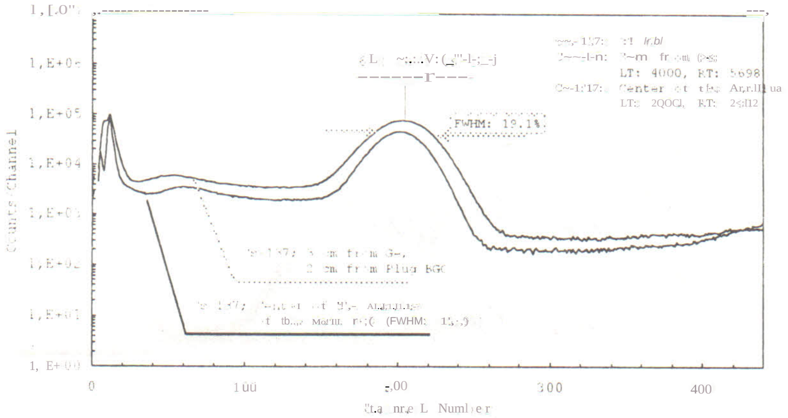


Fig. 1. [illegible] Distributions of Cs-137 with the [illegible] Detector [illegible] Main [illegible] at Two [illegible] Positions

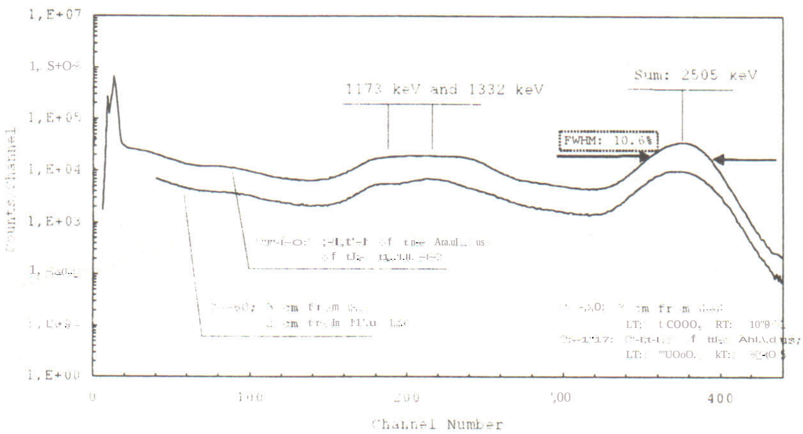
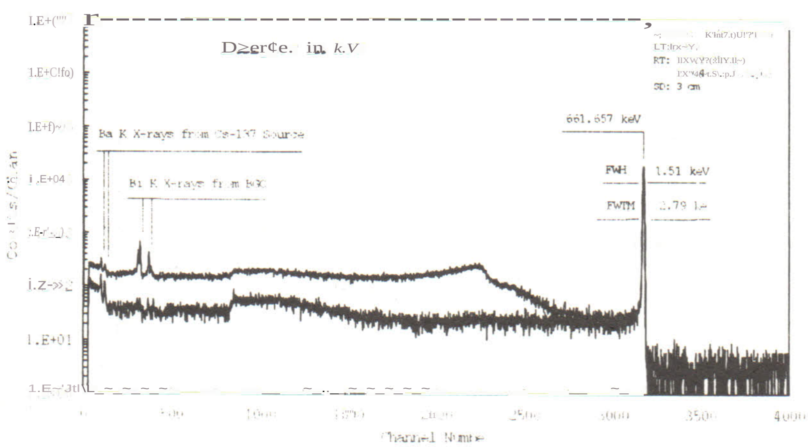


Fig. [illegible] Distributions [illegible] with the [illegible] Detector [illegible] Detector [illegible] Two [illegible] Positions



Fid. [illegible] Height Distributions [illegible] with [illegible] Spectrum [illegible]

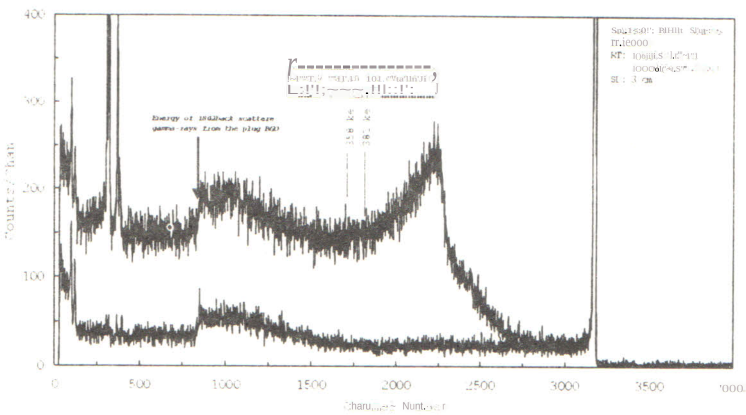


Fig. 6: Compton Spectra of Cs-137 Gamma-rays with and without the Compton Suppression Gamma-ray Spectrometer

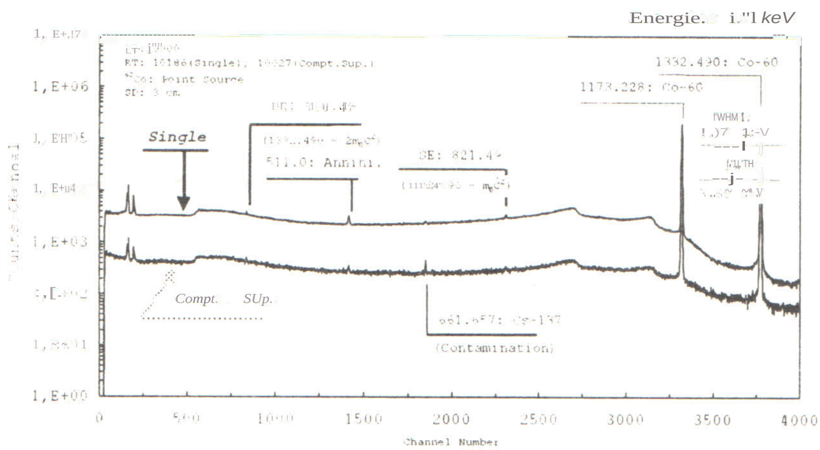


Fig. 7: Pulse Height Distribution of Co-60 Gamma-rays with and without the Compton Suppression Gamma-ray Spectrometer

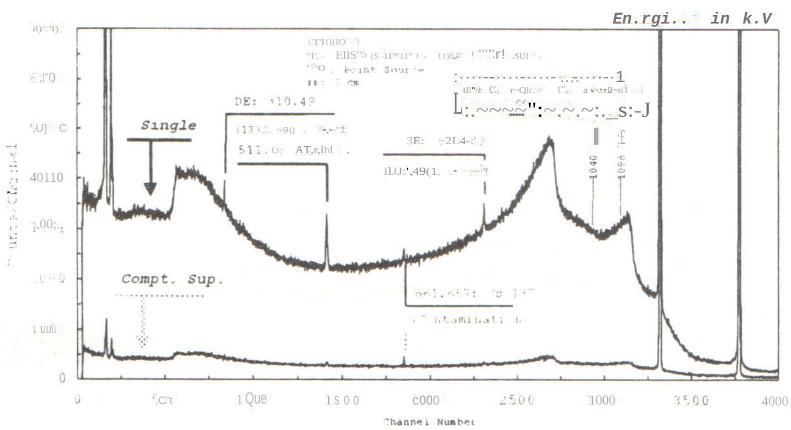
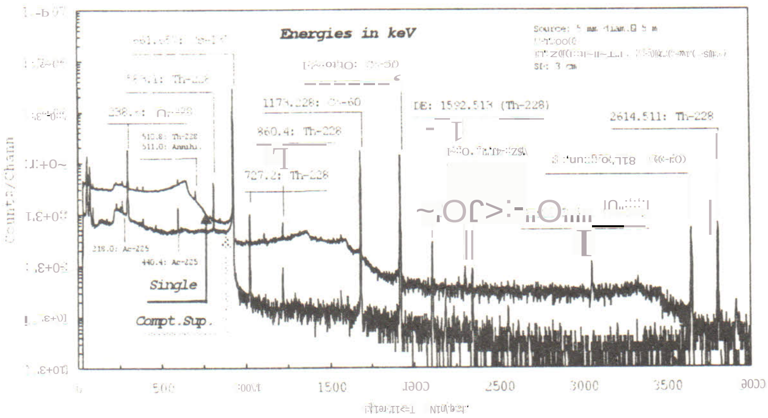
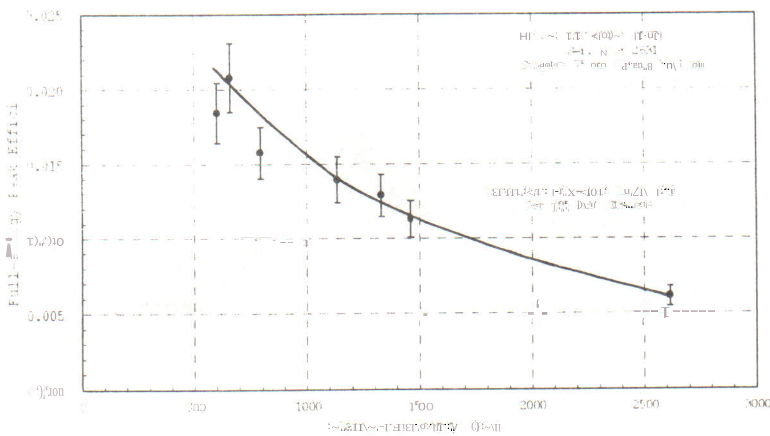
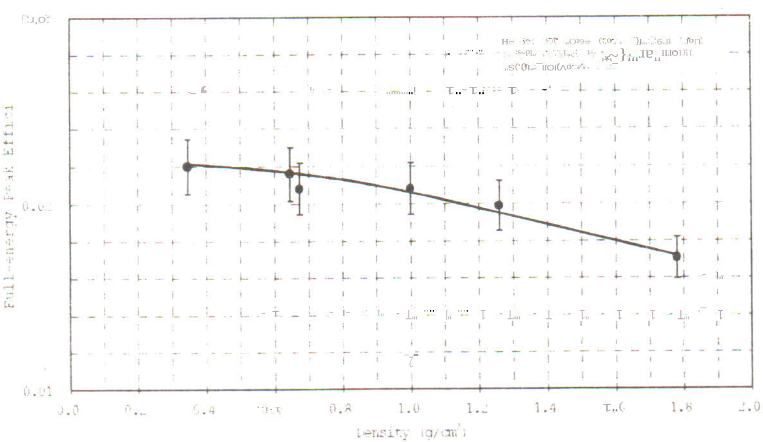
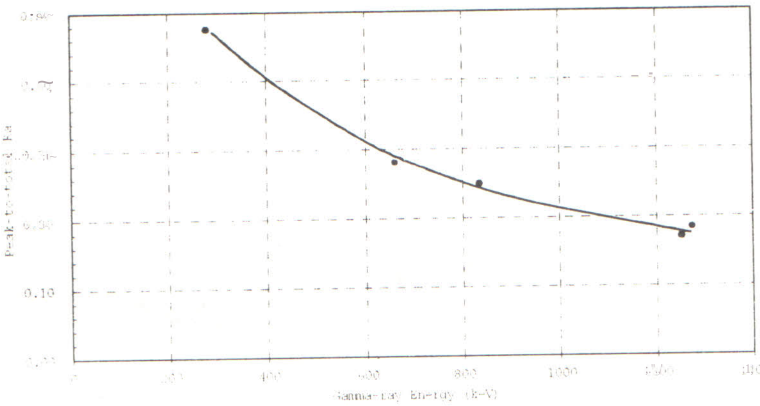


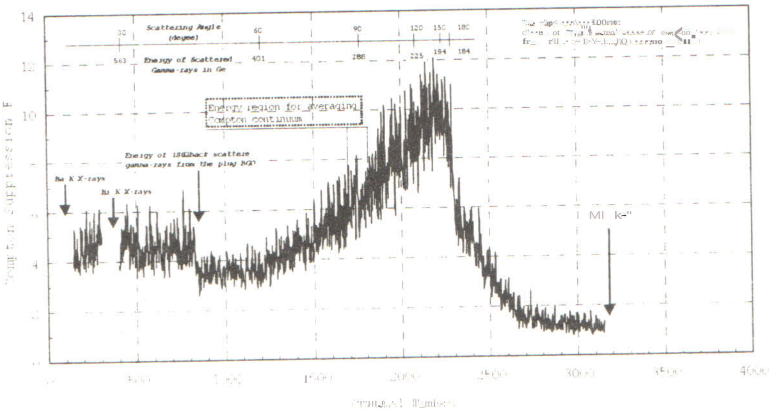
Fig. 8: Compton Spectrum of Co-60 Gamma-rays with and without the Compton Suppression Gamma-ray Spectrometer

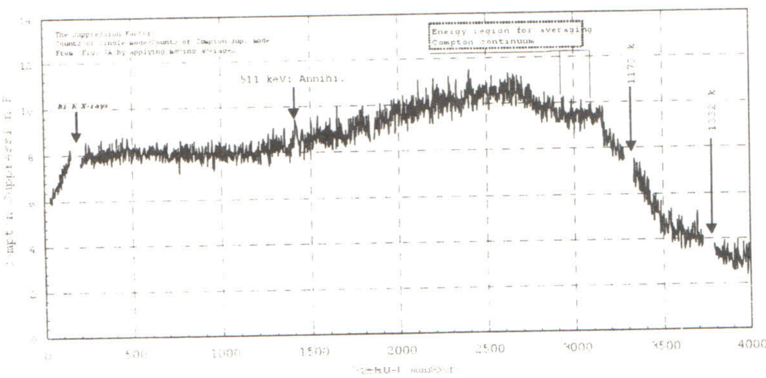

Energies in keV
2614.511: Th-228
1173.228: Co-60
860.4: Th-228
727.2: Th-228
Single
Compt.Sup.
Counts/Chann


0.005
0.020
1000
2000
2500
3000


Full-energy Peak Effici
Density (g/cm³)
0.01
0.4
0.8
1.0
1.4
1.8
2.0


0.10
200
400
600
800
1000


Scattering Angle (degree)
30
60
90
120
150
180
563
401
288
225
194
184
Energy of Scattered Gamma-rays in Ge
Energy region for averaging Compton continuum
Bi K X-rays
MI K
14
12
10
500
1000
1500
2000
2500
3000
3500
4000


Energy region for averaging Compton continuum
511 keV: Annihi.
Bi K X-rays
500
1000
1500
2000
2500
3000
3500
4000

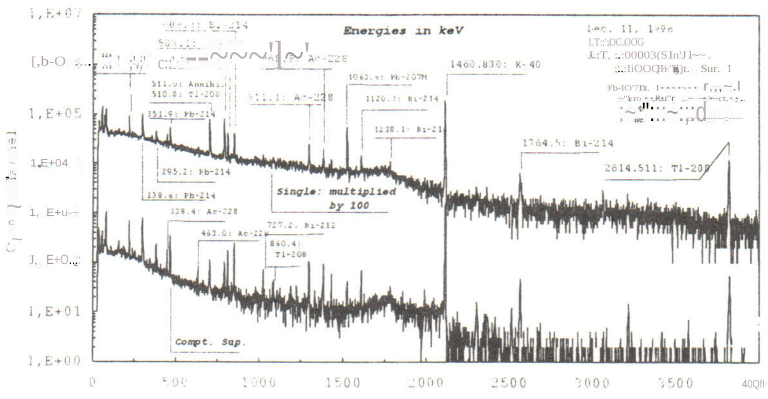


Fig. 14 Pulse Height Distributions of Natural Background with and without the Ge-BGO Compton-suppression Gamma-ray spectrometer

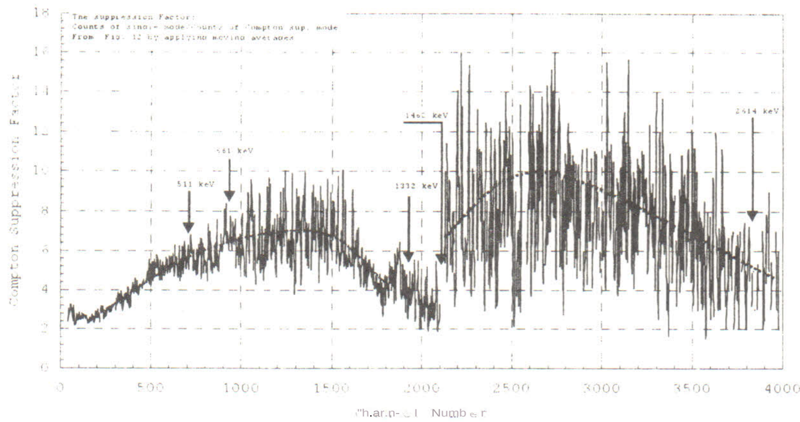


Fig. 15 [illegible] Factor [illegible] Natural [illegible]

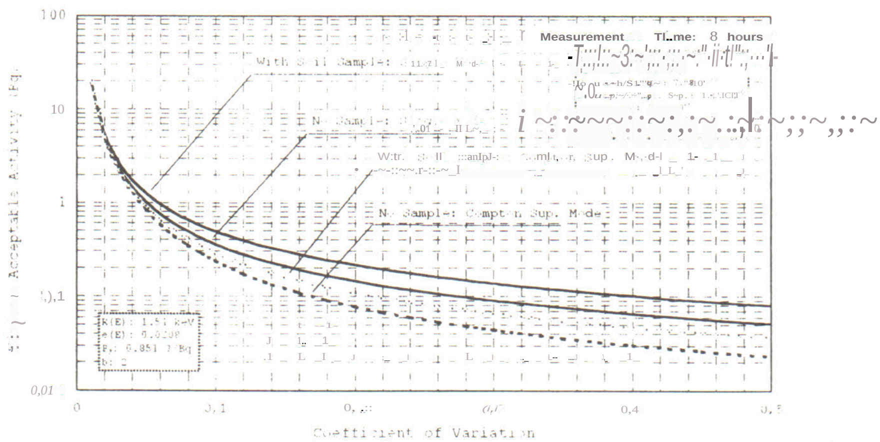


Fig. 16 [illegible] of [illegible] as a Function of [illegible] Coefficient of Variation (Measurement Time [illegible])

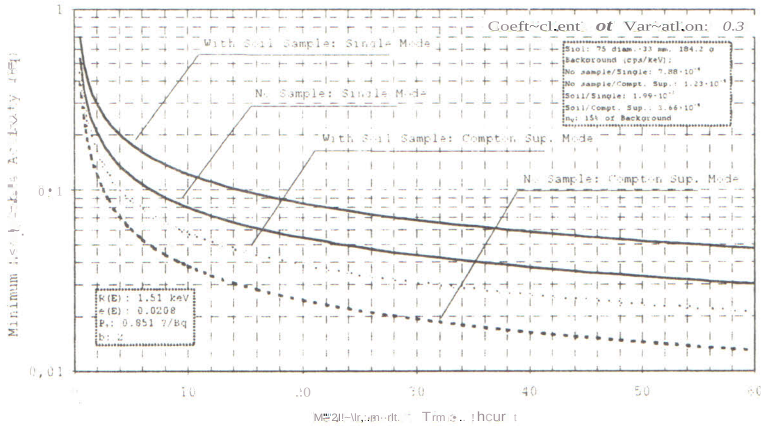


Fig. [illegible] Minimum Ac[illegible] [illegible] of [illegible] [illegible] Function [illegible]
[illegible] (The coefficient of variation: 0.[illegible])

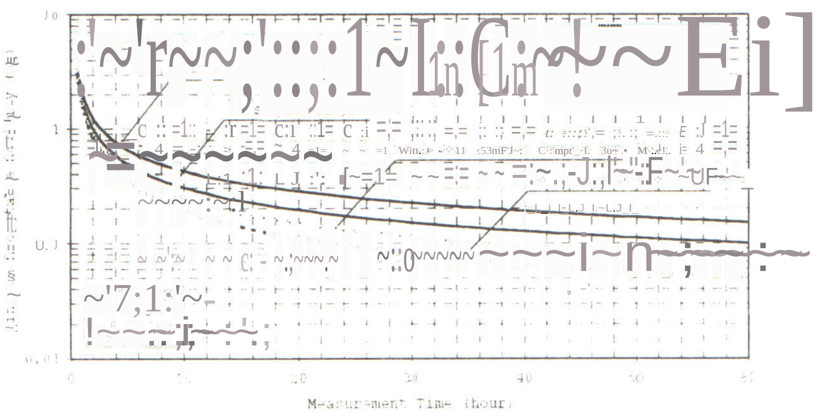


Fig. [illegible] Minimum [illegible] [illegible] [illegible] Function [illegible]
Measurement Time (The coefficient of variation: 0.1)