IMPACT OF COLLIMATOR AND ABSORBER ON THE SPECTRA MEASURED WITH HIGH PRESSURE XENON GAMMA-RAY SPECTROMETER PROTOTYPE

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The paper investigates the possibility in principle of determining the nuclide composition and activity of gamma-sources by analyzing the measured gamma-spectra provided an absorber installed between the gamma-sources and a xenon gamma-spectrometer placed in a cylindrical lead collimator.

Keywords: *isotope, gamma spectrometer, nuclear physics facilities, Compton effect, energy spectrum, xenon, radioactive waste, characterization of radioactive waste.*

Introduction

There are three different approaches that can be used to calculate the multiple scattering profile in gamma ray Compton studies. The first one suggests that the geometry of a scattering body is changed in a way that the proportion of events associated with more than one scattering decreases. In this case, a most obvious approach is to measure several absorber samples (in this case, soil) varying in their thickness and then extrapolate these results to their zero value. However, this method appears to be inapplicable, since the functional dependence of multiple scattering on the absorbing samples is quite complex and nonlinear even in case of relatively thin layers.

The second approach suggests that the multiple scattering profile can be estimated directly using the offset beam method avoiding single scattering. However, its geometry depends on the offset degree. Thus, extrapolation to zero should be accounted for if this method is used to calibrate multiple scattering.

Finally, under the third approach, one may calculate the intensity and spectral distributions of gamma ray multiple scattering. Its experimental parameters can be used in calculations to calibrate the measured Compton scattering profile.

These studies may provide accurate measurement data on the isotopic composition and activity levels of radioactive waste (RW) [1], [2] and contaminated materials that resulted from the operation of nuclear physics facilities and accidents of different severity levels [3], [4].

Experimental unit

A xenon gamma spectrometer (XGS) manufactured by the National Research Nuclear University MEPhI is a pulsed ionization chamber filled with compressed xenon Xe (Z = 54). In this study, a XGS with a capacity of 2,000 cm^3 is used [5]. Table 1 presents its main physical and technical characteristics.

Table 1. Main physical and technical characteristics of the XGS unit

Density of the working substance (xenon), g/cm^3	(0.3–0.4)
Range of measured gamma ray energies, MeV	0.03–3
Energy resolution for gamma quanta energy of 662 keV, %	1.9 ± 0.3
Registration efficiency of gamma quanta with the energy of 662 keV, %	2
Working capacity, cm^3	2,000
Weight, kg	5
Dimensions, cm	Ø15 × 45
Power consumption, W	20
Supply voltage, V	24
Operating temperature range, °C	0 – +90
Range of vibration-acoustic loads, dB	Up to 90
Linearity of the energy scale, %	<1 %
Service life, years	over 10
Radiation resistance, ability to work with neutron fluxes, neutron/s·cm^2	≈40

The above table demonstrates the high energy resolution levels inherent in XGS designs. In particular, assuming a gamma ray energy of 662 keV it accounts for (1.9±0.3)%, which is several times better than the one of popular scintillation detectors based on NaI(Tl) crystals. Figure 1 presents the XGS with a working capacity of 2,000 cm^3, namely, its schematic layout and a photograph.

In the energy range of 30—3,000 keV, the XGS's integral nonlinearity accounts for less than 1 %, i. e., to process the experimental XGS data, there is no need to use complex software to restore the measured gamma spectra and bring them to a linear energy scale. Typically, such software is used to process the measurements obtained from scintillation detectors, since their integral nonlinearity in the specified energy range prevents the use of linear calibration.

In case of neutron irradiation, no changes in the gamma line position of the gamma sources detected by XGS is observed neither any deterioration in the energy resolution assuming background neutron fluxes of up to 40 neutrons/(s·cm^2).

Xenon gamma spectrometer can operate jointly with a digital electronics unit in an environment with an acoustic load level of up to 90 dB provided no deterioration in the energy resolution [5].

High XGS stability ensures its long service life. The Ksenia gamma spectrometer operated for over a decade on board of the MIR orbital station as part of the Buket scientific equipment [6] with literally no changes detected in its key performance indicators.

Another specific advantage accounts for XGS's spectrometric characteristics that only slightly depend on the working capacity of the gamma detector with its dimensions that may range from 200 to 6,000 cm^3. This property has been repeatedly tested on its existing prototypes. In this regard, the actual dimensions of a XGS intended for various applications primarily depend on the specific tasks and conditions of their application.

It should be also noted that this detector can be manufactured at a much lower cost compared, in particular, to germanium or CZT semiconductor detectors with an identical sensitivity.

The above XGS properties indicate that it can be used to detect and identify radioactive and fissile materials, as well to implement relevant measurements along the RW management and NPP decommissioning process.

The spectrometer can be handled and the experimental data processed remotely in a real time

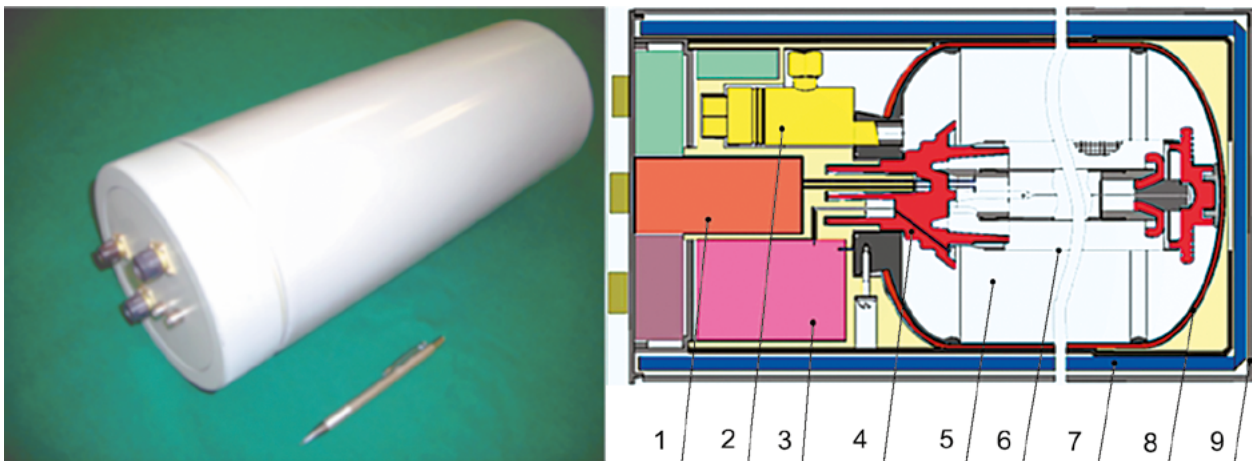

Figure 1. Photo and layout of the XGS: 1 — charge-sensitive amplifier, 2 — tap supplying the working substance, 3 — high-voltage power supply, 4 — ceramic sealed lead-in, 5 — ionization chamber, 6 — shielding mesh, 7 — Teflon insulation, 8 — steel housing with composite coating, 9 — outer protective casing

using a personal computer. Discussed below are the handling methods and algorithms implemented to analyze the data coming from the XGS.

Compton valley in the spectra measured by XGS

It is known that in the energy spectrum, the gamma source's photopeak does not change its position, even though the source is located behind an obstacle. However, the total number of events in the Compton valley region [7] may change considerably depending on the gamma radiation absorbers, namely, their size.

The best method developed to date to determine the geometric type of radioactive contamination sources is the analysis yielding the ratio between the detected scattered and unscattered components of the gamma source radiation in the measured instrumental spectrum. In this case, the most promising method accounts for the spectrum part scattered in the region of the so-called Compton valley corresponding to a zone between the total absorption peak and the right edge of the Compton distribution (Figure 2).

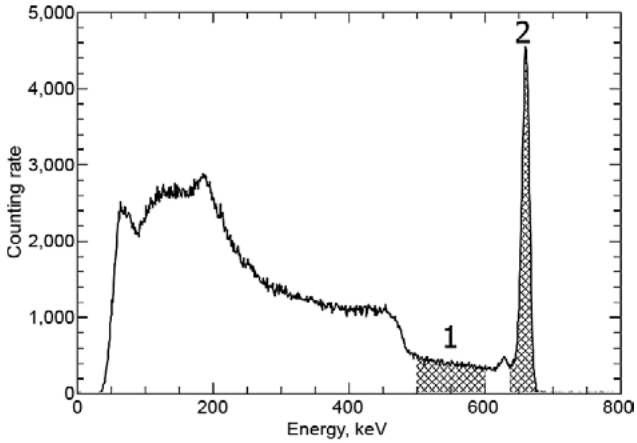

Figure 2. The Compton valley region (1) and the total absorption peak (2) as illustrated by the ^{137}Cs spectrum measured by a gamma-ray detector based on compressed xenon

For a monoenergetic source, pulses in the Compton valley region arise either from multiple Compton scattering or from interactions with the photons experiencing small-angle scattering (in the source material or in intermediate materials) before entering the detector causing total energy loss by them. Single interaction in the detector provides no opportunities for the unscattered photons from a monoenergetic source to form pulses in the Compton valley. In more complex spectra, this part may involve some pulses formed due to Compton scattering of higher energy photons.

A series of experiments was implemented to explore more thoroughly the influence of various absorbers on the shape of the recorded gamma ray energy spectra. Their findings are presented below.

Measurement method

A radioactive source of the OSGI ^{137}Cs type was fitted at a distance of 100 cm opposite the end of the xenon gamma detector (XGD). To reduce the detection of secondary scattered gamma radiation, the XGD was placed into a cylindrical lead collimator with a wall thickness of 3 cm and a diameter of 20 cm (Figure 3).

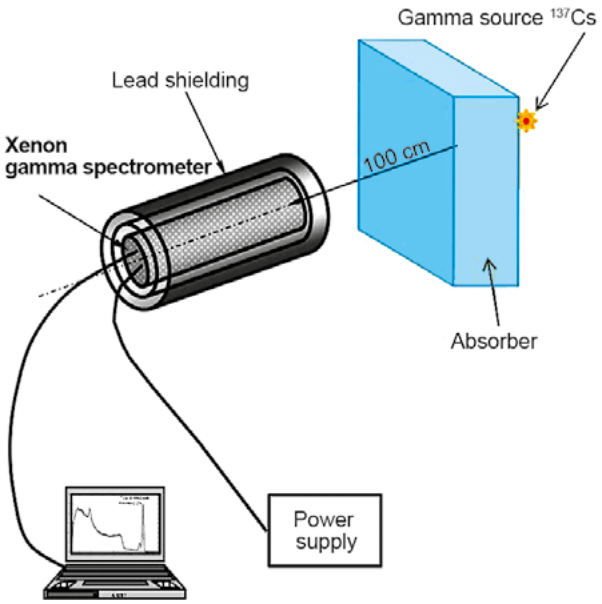

Figure 3. Layout of a unit designed to assess the potential of xenon gamma spectrometer application in identifying the geometric type of radioactive contamination sources

The measurements provided for two different XGD layouts in the collimator:

1) the end of the XGD was aligned with the edge of the collimator;

2) the detector was recessed into the cylindrical collimator by 20 cm, thus shielding it from scattered gamma rays formed due to its interaction with the absorber.

A ground absorber (soil) was used to observe the changing shape of the gamma spectrum, especially in the Compton valley region: it was installed between the ^{137}Cs gamma source and the XGD. The absorber thickness in the experiments varied accounting for 0 (no absorber), 5, 10 and 20 cm. The ^{137}Cs gamma radiation source had an activity level of 1 MBq.

Before the measurements of the energy spectra from gamma sources were launched, the energy scale of the gamma spectrometer was calibrated

and the background level was determined in the laboratory.

Experimental measurement results for the Compton valley

Each time before launching an experiment, background gamma radiation in the working area had been measured: it was further accounted for when processing the experimental data. One of these spectra is presented in Figure 4 clearly showing the characteristic gamma lines from natural radioactive isotopes: ^{40}K (1,460 keV) and ^{228}Th (2,614 keV).

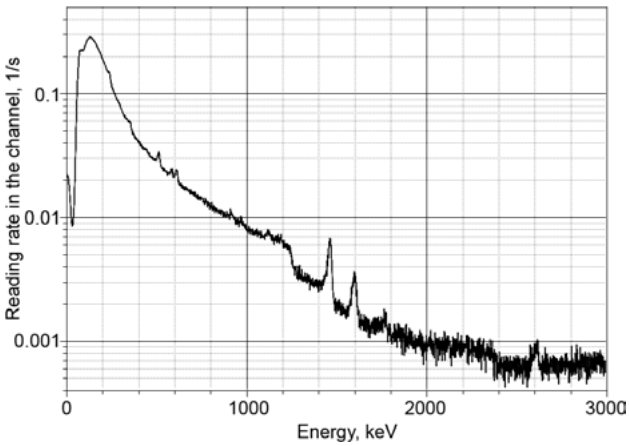

Figure 4. Spectrum of background gamma radiation in the working area

Figure 5 shows the energy spectra measured by the XGS assuming soil layers of various thicknesses, as well as the background gamma radiation spectrum.

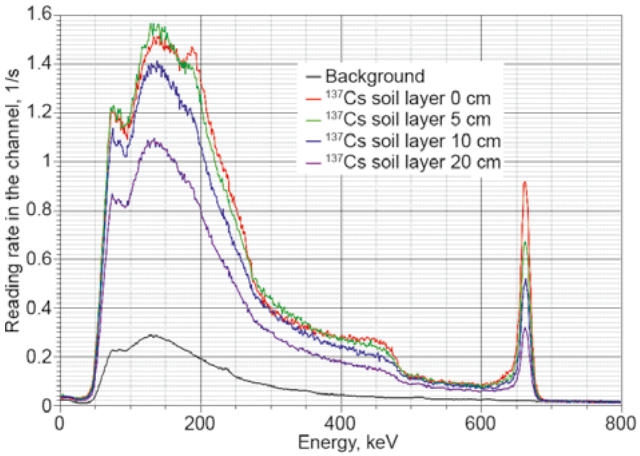

Figure 5. Spectra from a ^{137}Cs source with absorber layers (soil) of various thicknesses and background gamma radiation

Figure 6 provides more detailed representation of the changes occurring in the Compton valley depending on the soil layer thickness also showing the measured spectra from the ^{137}Cs source with the background subtracted and normalized to the total absorption peak area.

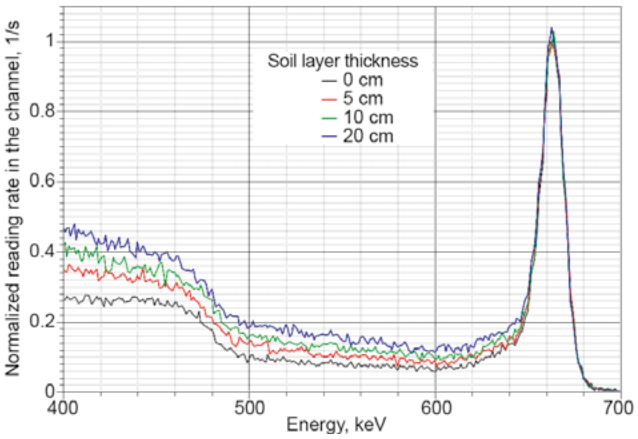

Figure 6. Changes in the Compton valley depending on the soil layer thickness

Higher thickness of the absorbing layer provided relative increase in the Compton valley area, which was selected in the gamma ray energy range from 500 to 600 keV.

To quantify this effect, the areas of the total absorption peaks (S_{peak}) and the Compton valley (S_{valley}) were calculated in each spectrum. Figure 7 presents the results obtained.

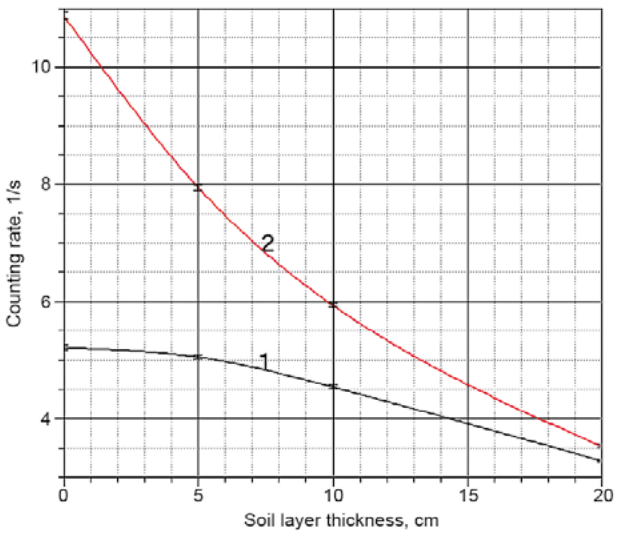

Figure 7. Dependence between the Compton valley (1) and the total absorption peak (2) areas and the soil thickness

The area ratios corresponding to the total absorption peaks and the Compton valley (S_{peak}/S_{valley}) have been calculated as well depending on the soil layer thickness. The area accounting for the Compton valley was calculated in the range of

500—600 keV, and the total absorption peak was calculated based on an approximation by a Gaussian distribution (Figure 8).

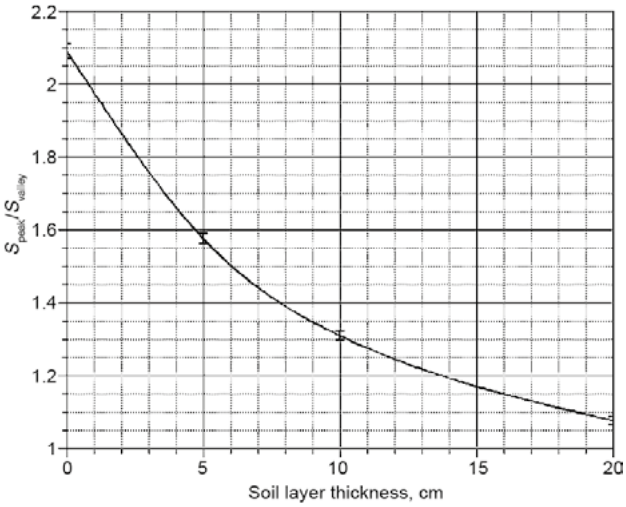

Figure 8. The area ratios corresponding to the total absorption peaks and the Compton valley (S_{peak}/S_{valley}) depending on the soil layer thickness

Figure 8 shows that based on the S_{peak}/S_{valley} ratio one may calculate the depth of a gamma radiation point source.

To evaluate this possibility, gamma spectra were measured from a ^{137}Cs source shifted relative to the central axis of the detector assuming soil layers of various thicknesses (0, 5, 10 cm). The experiments accounted for two positions: the end parts of the detector and the protection located in the same plane (position 1) and the end part of the detector deepened relative to the end part of the protection by 20 cm (position 2).

Figures 9—11 show the dependences between two areas: the one of the total absorption peak and the Compton valley, and their ratios (S_{peak}/S_{valley}) accounting for various source displacements relative to the central axis of the detector depending on the soil layer thickness. The detector was installed in position 1.

Figures 12—14 show the dependences between two areas: the one of the total absorption peak and the one of the Compton valley, and their ratios (S_{peak}/S_{valley}) depending on the source displacement relative to the central detector axis assuming various soil layer thicknesses. The detector was installed in position 2.

When the detector remained in position 1, the S_{peak}/S_{valley} ratio was depending slightly on the source shifting relatively to the central axis of the detector: thus, it could be used to estimate the depth of the distributed gamma radiation sources of up to 1 m.

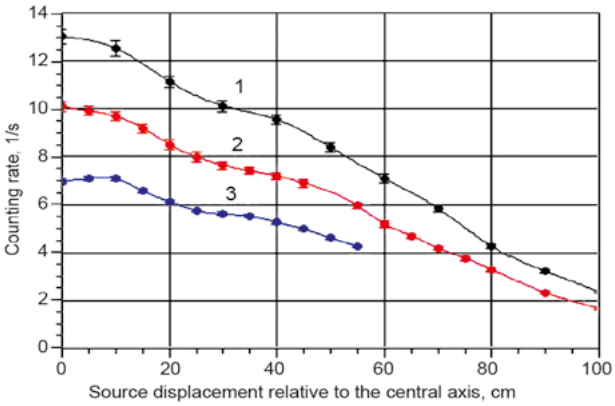

Figure 9. Dependence of the total absorption peak area on the source displacement relative to the central axis of the detector assuming different soil thicknesses: 1 — without soil, 2 — 5 cm of soil, 3 — 10 cm of soil. Detector — in position 1

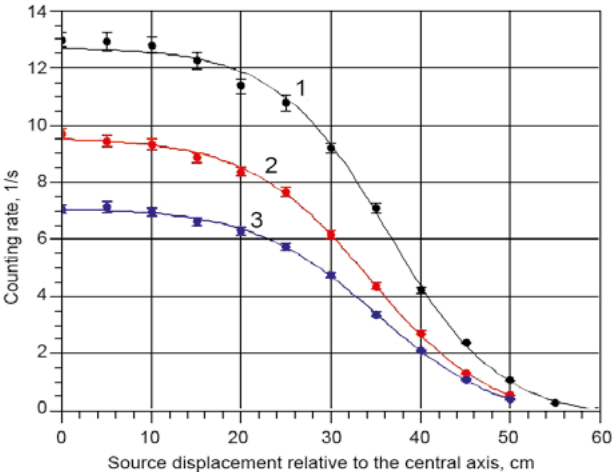

Figure 10. Dependence of the Compton valley area on the source displacement relative to the central axis of the detector assuming different soil thicknesses: 1 — without soil, 2 — 5 cm of soil, 3 — 10 cm of soil. Detector — in position 1

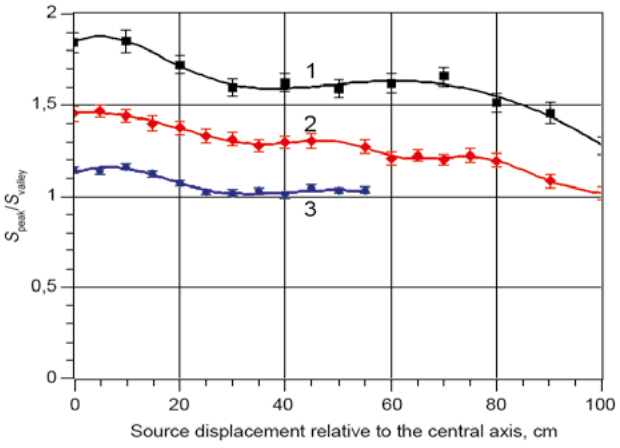

Figure 11. Dependence between the total absorption peak and the Compton valley area ratios (S_{peak}/S_{valley}) and source displacement relative to the central axis of the detector assuming soil layers of different thickness: 1 — without soil, 2 — 5 cm of soil, 3 — 10 cm of soil. Detector — in position 1

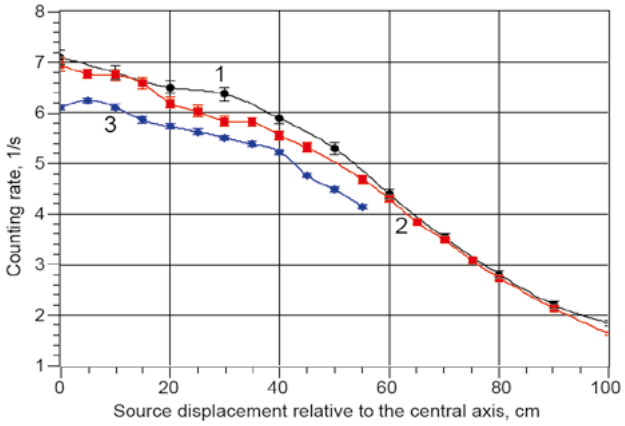

Figure 12. Dependence of the total absorption peak area on the source displacement relative to the central axis of the detector assuming different soil thicknesses: 1 — without soil, 2 — 5 cm of soil, 3 — 10 cm of soil. Detector — in position 2

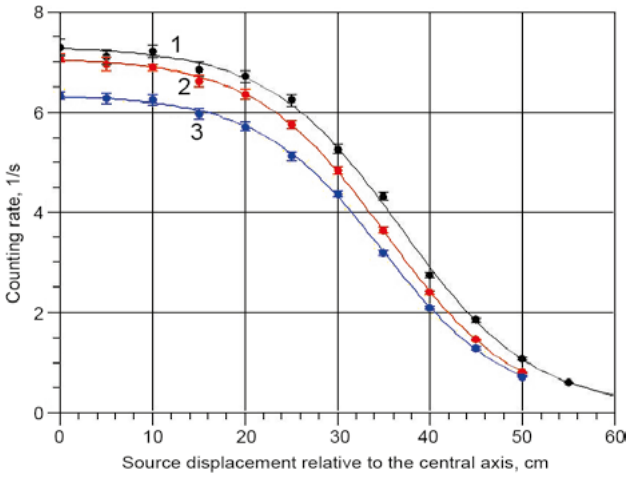

Figure 13. Dependence of the Compton valley area on the source displacement relative to the central axis of the detector assuming different soil thicknesses: 1 — without soil, 2 — 5 cm of soil, 3 — 10 cm of soil. Detector — in position 2

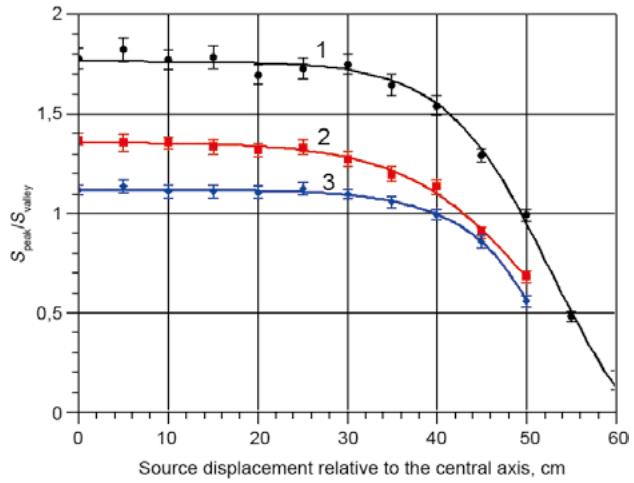

Figure 14. Dependence between the total absorption peak and the Compton valley area ratios (S_{peak}/S_{valley}) and source displacement relative to the central axis of the detector assuming soil layer of different thickness: 1 — without soil, 2 — 5 cm of soil, 3 — 10 cm of soil. Detector — in position 2

If the detector remained in position 2, the S_{peak}/S_{valley} ratio was depending slightly on the source shifting relative to the central axis of the detector only at a distance of up to 40 cm, corresponding to the field of vision: thus, it could be used in this range to estimate the depth of distributed gamma radiation sources.

As follows from Figures 12—14, the photopeak of the ^{137}Cs gamma source retained its position. However, the number of events in the total absorption peak varied depending on the soil layer thickness placed between the XGD and ^{137}Cs. Thus, the peak area can still be used to estimate the source depth until the number of events in it drops to the background level.

Conclusion

The experiments showed that a specific method can be developed to measure the thickness of an absorber installed between the XGS and the gamma source and to measure the gamma source activity and its radionuclide composition, thus providing more accurate data on the source location under radiation surveys and when evaluating the amount of radioactive waste generated from nuclear decommissioning. In practice, such absorbers may be represented by walls made of concrete, brick, stainless steel and other materials.

Absorption coefficients can be used to identify their construction material. These are calculated based on the processed data on measured spectra.

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Bibliographic description

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