GAMMA LOCATOR TO DETERMINE SPECTRUM CHARACTERISTICS OF QUANTUM FLUX

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ABSTRACT A gamma locator designed to conduct contamination surveys inside buildings connected with nuclear production has been developed. The device consists of a detector head and remote control unit connected with a cable (>100 m). The detector head (500 x 500 x 400 mm^3; the weight is near 40 kg) is a collimated scintillated gamma detector installed on a scanning unit. The gamma detector is placed in lead shielding with the collimator having an entrance angle near 10º. The detector head contains a TV camera and laser distance device. The remote control unit provides operation and processing of the acquired information. The gamma detector is based on a system of scintillator CsI(Tl) and Si photodiode. The detector energy resolution (it's near 9% for radiation of Cs-137) provides identification of gamma radiating isotopes such as Co-57, Cs-137, K-40, Co-60, I-131, and Eu-154. The gamma locator threshold of determination is 250 Bq/cm^2 for a 10 cm^3 scintillator and Cs-137 radiation. The system allows one to measure the effective surface activity density (for Cs-137 radiation) of all building surfaces and to reconstruct the exposed dose rate distribution within the volume of investigated space.

KEYWORDS: contamination survey, gamma radiation, collimated scintillated detector, scintillator, photodiode

INTRODUCTION

Many nuclear reactors and industrial facilities will reach the end of their design lifetimes in the last decade of this century. A lot of equipment and components are radioactive during their operation periods. Especially of concern are components of the primary systems of nuclear reactors. Decontamination and decommissioning of these facilities require one to identify the radioactive materials, to estimate the activity of each radionuclide, and to locate radionuclide distribution in the systems and components. Dose rates in these buildings and areas are defined by direct-radiation from contaminated equipment as well as radiation scattered by concrete walls and other components in the area. Usual dosimetry techniques (integrating dosimeters) do not permit one to identify and locate the radiation sources with sufficient accuracy to allow planning of the decommissioning and decontamination activities.

New devices are needed which can be used remotely to locate gamma radiating sources, to measure activity distributions of radioactive materials, and to measure energy spectra of quantum flux in complex situations. Portable gamma-ray detectors with imaging capability in the energy range of 100 keV to a few MeV are required for a number of applications in nuclear industry, such as monitoring in nuclear power plants, radioactive distribution measurements for nuclear material inspections and radiation surveillance in accident situations, and decontamination and decommission activities. Devices based on the collimated gamma detector technique have been developed in a number of laboratories [1-3].

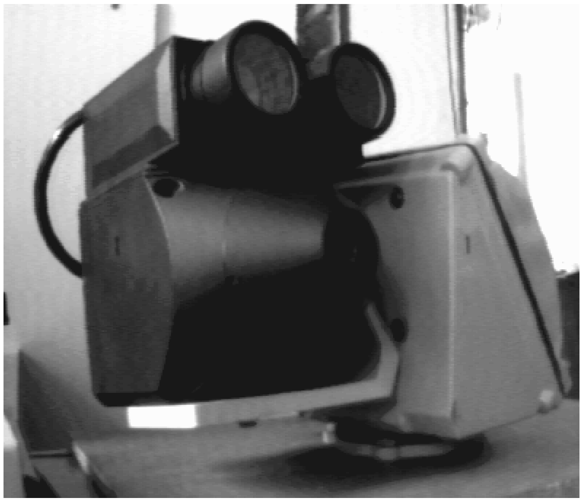

FIGURE 1. MEASURING HEAD OF GAMMA LOCATOR.

This report provides details on a collimated spectrometric scintillated gamma detector (gamma locator) provided to map contamination, to measure spectra of gamma radiation, to calculate dose rate distribution inside the contaminated areas, and to predict optimal decontamination consequences. Manual prototypes of this system were used in autumn 1986 for search and identification of intense gamma radiated sources in and around the Chernobyl NPP Unit No. 4 [4-6]. The computer control device version measured contamination distribution and reconstructed dose rate distribution inside a machine building of the 4th Unit ChNPP [7-8].

DEVICE CONSTRUCTION

The gamma locator is an automatic computer-controlled measuring system intended for gamma radioactive object mapping, energy spectrum determination, and dose rate distribution reconstruction. It consists of a measuring head and control unit. The measuring head may be removed from the control unit up to a 100 m distance and is connected by a cable (the cable length is 100 m). The gamma locator registers the flux of gamma quanta defined by the solid angle of the collimator. The registered flux of quanta is related to effective surface activity density in cases of surface contamination or to specific activity density in cases when there is a volumetric source of radiation. By measuring of energy spectra of a quantum flux, the information about the gamma radiating radionuclide is obtained and the distribution of exposed dose rate (EDR) for individual radionuclides can be calculated.

Figure 1 shows the measuring head. It consists of a lead-shielded gamma detector; computer-controlled scanning unit; TV camera, allowing one to observe the radiating area; a laser distance device, determining the distance between the collimated detector and measuring object; interface maps of scanning unit positioning control; and the signal-registering unit of the gamma detector. To receive and process energy spectra of gamma radiation a 256-channel analyzer is used.

The developed software allows one to control all units of the system, to superimpose visible images of the contaminated area and contamination levels, to present superimposed images and measured information on computer screen, and to process spectra and all other measured data.

The software calculates the distribution of EDR in the whole volume of the measured area and forecasts optimal consequences of decontamination and its efficiency.

Currently two prototypes of the system have been developed. The first one has the following parameters:

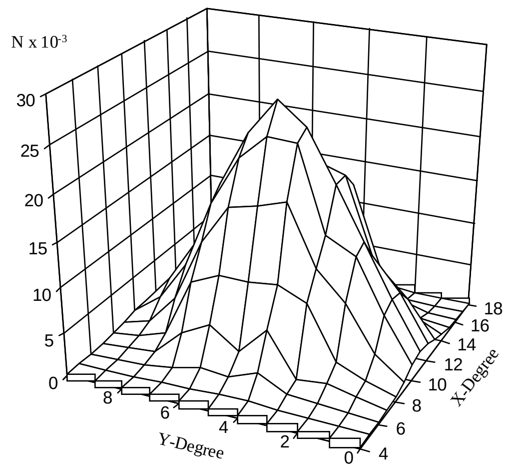

FIGURE 2. ANGULAR APPARATUS FUNCTION FOR LARGE DETECTOR.

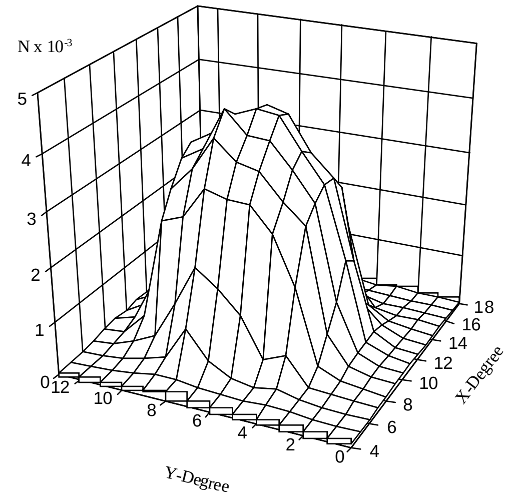

FIGURE 3. ANGULAR APPARATUS FUNCTION FOR SMALL DETECTOR.

- total weight of measuring head is less than 30 kg; the scanning unit weight is 10 kg;
- scintillated crystal CsI (Tl) with the sizes 10 x 10 x 10 mm^3;
- dimensions of the collimator with exchangeable inserts:
  length 55 mm, diameter 11 mm;
  length 110 mm, diameter 11 mm;
  length 55 mm, diameter 3 mm;
- energy resolution is near 8% for Cs-137 radiation (662keV);
- minimum detection Cs-137 surface activity is 1,000 Bq/cm^2 for the largest collimation angle; the determined point of source activity is near 4 x 10^7 Bq at 10 m distant. This system was extensively tested and is used as a part of the equipment for nuclear emergencies now.

The second one was developed especially for conditions of the 4th Unit of Chernobyl NPP and has an extended measuring range for intensive radiation situations. To increase the measured range inside intensive quantum flux, two exchangeable detectors are used. Each detector consists of a scintillated gamma detector, collimator, preamplifier, and shape amplifier in a common body. The following detectors and collimators are used:

- crystal CsI(Tl) with sizes ϕ8 mm x 20 mm and collimator with sizes ϕ9 mm x 90 mm;
- crystal CsI(Tl) with sizes ϕ8 mm x 2 mm and collimator with sizes ϕ2 mm x 20 mm. The collimator works as a diaphragm in the last case to reduce the quantum flux in high radiating areas.

The small size preamplifier and shape amplifier have been developed and placed inside a lead shield. This construction protects the chips from radiation.

Typical apparatus functions for Chernobyl detectors are shown in Figures 2 and 3. The gamma locator scans the space in the center of the point at which the Cs-137 source is located. The angular step of scanning is 1º in the vertical and horizontal planes and the count rate is measured. One can see that the accuracy of the scanning unit is 1º and it is not sufficient to provide angular measurements better than 2º. The efficiency

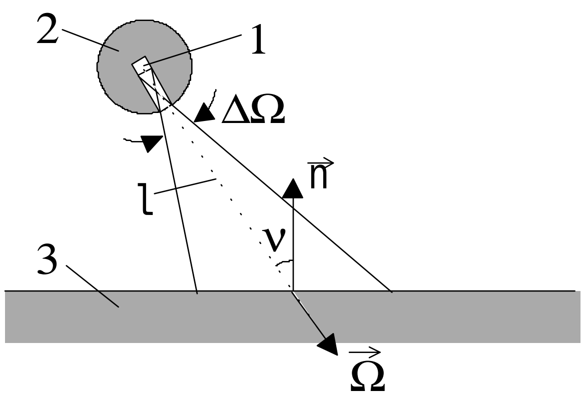

FIGURE 4. GEOMETRY OF MEASUREMENTS BY THE COLLIMATED DETECTOR: 1 = DETECTOR, 2 = SHIELD AND COLLIMATOR OF THE DETECTOR, 3 = SURFACE, CONTAMINATED BY RADIONUCLIDES, $\Delta\Omega$ = EFFECTIVE SOLID ANGLE OF THE COLLIMATED DETECTOR, $\vec{\Omega}$ = DIRECTION OF THE COLLIMATOR AXIS, $\vec{n}$ = NORMAL VECTOR TO THE SURFACE, l = DISTANCE BETWEEN THE DETECTOR AND SURFACE ON THE DIRECTION OF THE COLLIMATOR AXIS.

of the sensitive detector is near 9% for the photo absorption energy range, and it is 10 times less for the small detector. The total sensitivity of the detectors differs by 50 measures of magnitude.

A large volume CsI(Tl) detector (≈10 cm^3) is under development now. To increase the light output from the crystal, its optimal shape was calculated. The optimal crystal shape is an ellipsoidal one and a photodiode should be placed at one of its foci. The optimal shape detector allows one to keep the energy resolution less than 9% and to increase the efficiency more than 5 times in comparison with a detector used in the developed collimated system. To keep an angular resolution, a multihole collimator has been manufactured.

The further variants of the developed collimated detector may be used as standard equipment to determine radioactive contamination.

SURFACE ACTIVITY MEASURING METHOD AND DOSE RATE CALCULATION

The gamma locator measures a count rate, N, corresponding to quantum flux inside the collimator view. It is proportional to surface activity, σ, in a case of surface contamination of building walls by gamma-emitting radionuclides (Figure 4):

$$N = \Phi\left(-\vec{\Omega}\right)\Delta\Omega\varepsilon\,, \tag{1}$$

where Φ = quantum flux in the direction of the collimator axis, ε = average efficiency of radiation registration of the detector inside solid angle ΔΩ.

For nonscattered quantum flux the equation follows:

$$\Phi = \frac{e^{-\Sigma(E)l}\sigma n_i}{4\pi\left|\vec{\Omega}\vec{n}\right|} = \frac{e^{-\Sigma(E)l}\sigma}{4\pi\cos\nu} n_i\,. \tag{2}$$

Here $\Sigma(E)$ = linear absorption factor in air; σ = surface activity of radionuclide, emitting gamma-quanta with energy, E; n_i = output of quanta given energy per one decay of the nucleus; l = distance between gamma locator and measured surface.

Uniting Equations 1 and 2, it may be written:

$$N = \frac{\sigma e^{-\Sigma(E)l}}{4\pi\cos\nu}\Delta\Omega\varepsilon n_i\,. \tag{3}$$

To take into account the influence of scattered radiation, one should use Equation 3 in the following form:

$$N = \frac{\sigma n_i e^{-\Sigma(E)l}}{4\pi\cos\nu}\Delta\Omega\varepsilon B\,, \tag{4}$$

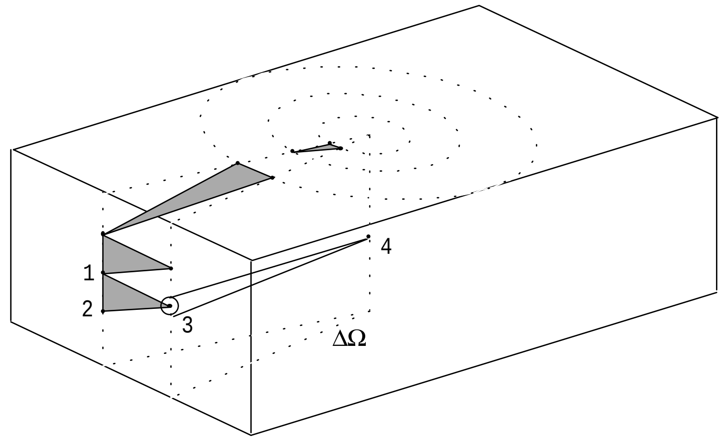

FIGURE 5. THE SCHEME OF SCANNING OF A BUILDING BY THE COLLIMATED DETECTOR: 1, 2 AND 3 = POINTS OF CROSSING OF THE COLLIMATOR AXIS WITH THE MEASURED SURFACE, 4 = POSITION OF THE DETECTOR.

where $\varepsilon B = \varepsilon_0 + \varepsilon_s \kappa$, ε_0, and ε_s = registration efficiencies of nonscattered and scattered radiations by the collimated detector, κ = part of scattered quanta (this radiation is the result of quantum scattering in air and reflecting of radiation from the contaminated surface).

Thus, using Equation 4, the surface activity may be determined as:

$$\sigma = \frac{4\pi}{n_i \Delta\Omega \varepsilon B} N e^{\Sigma(E)l} \cos\nu = \frac{const}{\varepsilon B} N e^{\Sigma(E)l} \cos\nu. \qquad (5)$$

The measuring method of surface activity in the contaminated building is based on Equation 5.

Assume that a collimated detector is inside a rectangular building (Figure 5) and automatically scans its surface with a certain angular step; i.e. it defines the number of registered gamma-quanta from a given angular direction in solid angle $\Delta\Omega$. The three nearest points of crossing of the collimator axis in the measuring point and of the building surface form a triangle (for example, points 1, 2 and 3 in Figure 5). The set of all these triangles creates a closed surface, presenting an approximation of the internal surface of building.

To determine surface activity of each of these triangles, it is possible to use the expression:

$$\sigma \cong \frac{const}{\varepsilon B} \frac{1}{m} \sum_{i=1}^{m} N_i \cos\nu_i e^{\Sigma(E) l_i} \quad (m = 3), \qquad (6)$$

which defines σ as average arithmetic significance of measurements N in triangle tops with an accuracy of a constant.

To find $\cos\nu_i$ the following expressions may be used. Suppose the collimated detector is at the center of coordinates, and vectors $\vec{r}_i = \{x_i, y_i, z_i\}$ (i = 1,2,3) define the tops of the considered triangle, i.e., points 1, 2 and 3 (Figure 5). Then

$$\cos\nu_i = \frac{(\vec{r}_i, \vec{p})}{l_i |\vec{p}|}, \quad i = 1,2,3, \qquad (7)$$

where $l_i \equiv |\vec{r}_i|$,

$$\vec{p} = \left[(\vec{r}_1 - \vec{r}_2), (\vec{r}_1 - \vec{r}_3)\right] = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_1 - x_2 & y_1 - y_2 & z_1 - z_2 \\ x_1 - x_3 & y_1 - y_3 & z_1 - z_3 \end{vmatrix}.$$

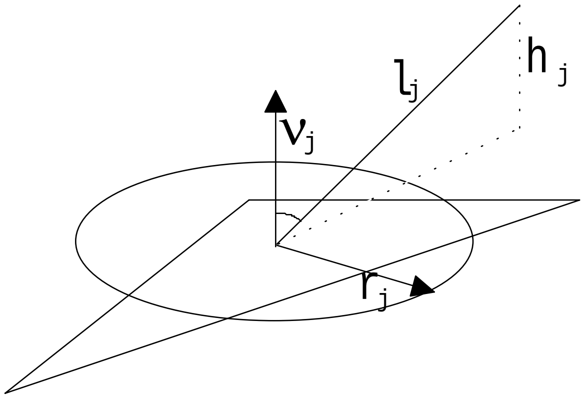

FIGURE 6. REPLACEMENT OF A TRIANGULAR SURFACE WITH A CIRCULAR ONE.

In this case the area of the given triangle equals

$$S = \frac{1}{2}\left|\vec{p}\right|.$$

From Equation 5, the calibration factor $4\pi/\Delta\Omega\varepsilon Bn_i$ is determined experimentally using a flat source with the known surface activity σ. If the collimated detector has $\Delta\Omega << 4\pi$, as a rule, part of the scattered quanta is not so significant. It permits one to believe that a calibration factor determined experimentally slightly differs from const/εB in Equation 6 for any approximating triangular surfaces of contaminated buildings.

Thus the results of scanning by the collimated detector of a contaminated building allow the distribution of surface activity of radionuclides to be determined.

It permits calculation of the distribution of dose rate inside this building also. To calculate the dose rate the following expression may be used

$$P = k\sum_{j=1}^{m}\sigma_j\eta_j e^{-\sum(E)l_j} B_{DJ}\ , \tag{8}$$

where k = factor of proportionality, σ = surface activity of j^{th} triangle, l_j = distance from the center of triangle to the point in which the dose rate is calculated, η_j = function, determining the contribution to dose rate of nonscattered radiation of the j^{th} triangular surface, B_{Dj} = the dose factor, taking into account the contribution to dose rate a scattered radiation of j^{th} direction, m = number of triangular surfaces.

In common for any triangular surface, η, is a multiparametrical function, depending on the form, size, and orientation of the considered triangle in space. Therefore for simplification of calculating procedures the considered triangular surface is assumed to be replaced by a circular surface with the same area (Figure 6).

For this surface [9]:

$$\eta_j = \begin{cases} \ln\left[\dfrac{2h_j^2 - l_j^2 + r_j^2 + \sqrt{r_j^4 + 2r_j^2\left(2h_j^2 - l_j^2\right) + l_j^4}}{2h_j^2}\right], h \neq 0. \\ \ln\left[\dfrac{l_j^2}{l_j^2 - r_j^2}\right], h_j = 0 \end{cases} \tag{9}$$

Here $h_j = l_j\ Cos\nu_j$, $r_j^2 = S_j/\pi$, S_j = area of triangle.

To define the factor k in Equation 8, it is necessary experimentally to measure the dose rate at the point by arrangement of the collimated detector. According to Equation 8 it is possible to write for the dose rate at this point:

$$P_0 = k\sum_{i=1}^{m}\sigma_i e^{-\sum(E)l_{0i}}\eta_{0i}B_{0D}\ , \tag{10}$$

One can find k from Equation 10

$$k = \frac{P_0}{\sum_{i=1}^{m}\sigma_i e^{-\sum(E)l_{0i}}\eta_{0i}B_{0Di}},$$

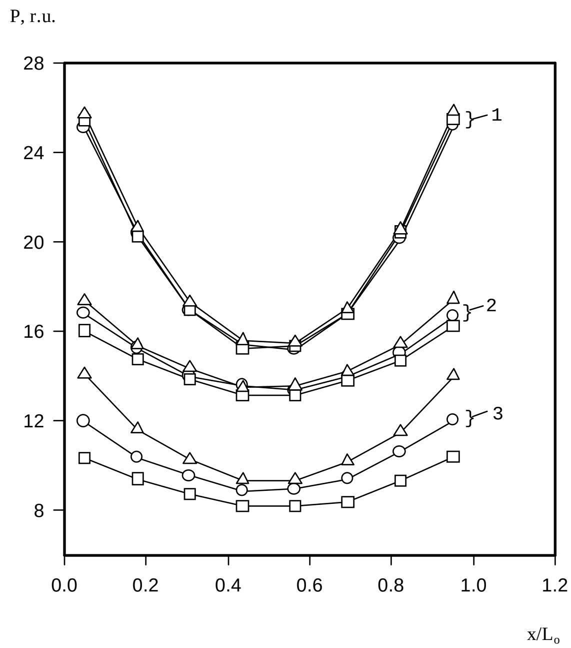

FIGURE 7. DISTRIBUTION OF DOSE RATE ALONG A DIAGONAL OF AN HOMOGENEOUSLY CONTAMINATED BUILDING OF THE CUBIC FORM WITH THE SIZE OF SIDE a: 1 = a = 10 m; 2 = 60 m; 3 = 200 m; $L_0 = a\sqrt{3}$ = LENGTH OF THE DIAGONAL. 0 = REAL DISTRIBUTION; □ = RESTORED ONE WITHOUT CONSIDERATION OF AIR ABSORPTION, THE TOTAL COUNT RATE IS MEASURED; Δ = RESTORED ONE WITH ABSORPTION IN AIR AND THE COUNT RATE IN PHOTO ABSORPTION RANGE IS MEASURED.

and for an arbitrary point the dose rate is determined by the formula:

$$P = \frac{P_0}{\sum_{i=1}^{m} \sigma_i e^{-\sum l_{0i}} \eta_{0i} B_{0Di}} \sum_{j=1}^{m} \sigma_j e^{-\sum l_j} \eta_j B_{0Dj} = \frac{\langle B_D \rangle}{\langle B_{0D} \rangle} \left[\frac{P_0}{\sum_{i=1}^{m} \sigma_i e^{-\sum l_{0i}} \eta_{0i}} \right] \sum_{j=1}^{m} \sigma_j e^{-\sum l_j} \eta_j \qquad (11)$$

In this expression $\langle B_D \rangle$ and $\langle B_{0D} \rangle$ are average dose factors, accordingly, for any point and location of the detector. Obviously, the significance of the relationship $\langle B_D \rangle / \langle B_{0D} \rangle$ for various points inside the building can be more or less and is, *a priori*, uncertain. However, if one sets this relationship equal to unity, he should estimate a methodological error of dose rate calculations. It depends on many factors, but the main of them is the point of dose rate definition. A special Monte-Carlo program has been developed to find out the value of this methodological error. The first part of it calculates dose rate distribution in a contaminated building of the given form and sizes; the other simulates the readings of the collimated detector in the selected building and then under the Equations 6, 9, and 11, the dose rate distribution is restored and compared with true (constructed under the first part of the program). The various approaches are considered; for example, the influence of the exponential factor in Equations 6 and 11 (the influence of radiation absorption in air), readings of the detector are evaluated by the count rate in the whole energy range or in the photo absorption one (in a peak of complete absorption) only, etc.

The accounts were carried out for cube-shaped building with sizes 10, 60, and 200 m. Dependencies of the dose rate on distance along the diagonal of the building, contaminated with surface activity σ, calculated by Monte-Carlo method, are shown in Figure 7. In this figure the reconstruction of dose rate according to Equations 6, 9, and 11 are shown also. The collimated detector for these calculations is placed in the center of the building at a height of 3 m over the floor level.

As a result of theoretical analysis it has been established that the methodological error of dose rate definition depends on many factors. In particular it depends on the size of the considered building, the collimated detector location inside it, the heterogeneity of building contamination (an approximation must be used), etc., but nevertheless for the majority of cases the methodical error of such approach does not exceed 30%. It permits one to use it for remote measurements inside a large size building in accident situations.

This approach has been tested at laboratory conditions for a simple known distribution of gamma emitting sources, and the calculated dose rate distribution coincides with the real one with error of less than 30%.

CONCLUSIONS

A gamma locator has been developed for use in intensive radiation conditions of the Chernobyl NPP 4^{th} unit. It has an extended measuring range; the exchangeable collimated detectors are used for this. The system has been tested in laboratory conditions. The gamma detector based on scintillated crystal and photodiode has 8% energy resolution for Cs-137 gamma radiation.

The special software calculates the surface activity of all surfaces of the contaminated building and then the dose rate distribution in the whole volume of it. The comparison of calculated dose rate distributions and measured ones shows a coincidence within 30% accuracy.

The detector with a scintillated crystal of more then 10 cm^3 increases the sensitivity of the gamma locator by more then 5 times and maintains the energy resolution of the detector. The detectable limit of the system may reach 100 Bq/cm^2 for Cs-137 contamination.

To increase the angular resolution and sensitivity of the gamma locator, several detectors may be used inside a common shield. It allows one to keep the energy resolution and to increase the angular resolution. From the other side, adding count rates from different detectors at one comparator allows one to increase the sensitivity of the gamma locator.

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