# An improved segmented gamma scanning for radioactive waste drums

LIU Cheng WANG Dezhong<sup>\*</sup> BAI Yunfei QIAN Nan

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

**Abstract** In this paper, the equivalent radius of radioactive sources in each segment is determined by analyzing the different responses of the two identical detectors, and an improved segmented gamma scanning is used to assay waste drums containing mainly organic materials, and proved by an established simulation model. The simulated radioactivity distributions in homogenous waste drum and an experimental heterogeneous waste drum were compared with those of traditional segmented gamma scanning. The results show that our method is good in performance and can be used for analyzing the waste drums.

Key words Segmented gamma scanning, Equivalent radius, Activity detection, Radioactive waste

## 1 Introduction

It is important to analyze accurately radioactive waste drums before their final disposal. Segmented gamma scanning (SGS) has been used for non-destructive determination of the activity of nuclear waste drums. SGS is based on the assumption that the drum matrix and radioactive sources are distributed uniformly in each vertical segment. Therefore, the systematic errors of the analysis are usually large due to non-uniform spatial distribution of the radioactive sources and a heterogeneous matrix<sup>[1,2]</sup>.

To improve accuracy of the SGS, each segment of a waste drum is divided into several rings, and activity of each ring is measured<sup>[3]</sup>. By rotating the drum, the dependence of angular distribution on the counting rate is recorded by 'hot spot' activity<sup>[4]</sup>. Additionally, tomographic gamma scanning(TGS) uses emission and transmission scans over the drum to yield three-dimensional images of density and activity distribution<sup>[5]</sup>.

In this paper, we report an improved segmented gamma scanning (ISGS) to analyze a drum containing mainly organic materials. The equivalent radius of radioactive sources in each segment is determined by two HPGe detectors at different positions. The ISGS

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performance is evaluated by the source distribution.

## 2 Theoretical basis

The ISGS assumes that the rotating drum is measured twice by two identical detectors, and each segment is in uniform linear attenuation coefficient (Fig.1). Detector A is aligned to the drum center, while Detector B is located at a distance of L from the axis of Detector A. Instead of a rotating point source, an equivalent ring source at the same detected response is used (Fig.2).







Fig.2 Replacing a point source with an equivalent ring source.

<sup>\*</sup> Corresponding author. *E-mail address*: dzwang@sjtu.edu.cn Received date: 2009-11-26

The counting rate of the two detectors from the segment,  $C_A$  and  $C_B$ , can be given by

$$C_{\rm A} = \alpha I_t \int_0^R p_r E_{\rm A}(r) dr \tag{1}$$

$$C_{\rm B} = \alpha I_t \int_0^R p_r E_{\rm B}(r) dr \tag{2}$$

where,  $\alpha$  is branching ratio of  $\gamma$ -rays; r is radial distance from the source to drum center; R is the drum radius;  $I_t$  is total activity of the segment;  $p_r$  is radial density of the activity; and  $E_A(r)$  and  $E_B(r)$  are photopeak efficiency of the source and are depended on geometry, attenuation matrix,  $\gamma$ -ray energy and the detection efficiency.

Then, one has,

$$\frac{C_{\rm B}}{C_{\rm A}} = \frac{\int_0^R p_r E_{\rm B}(r) dr}{\int_0^R p_r E_{\rm A}(r) dr}$$
(3)

If  $F(r)=E_{\rm B}(r)/E_{\rm A}(r)$  is monotone from 0 to R, one has  $F(r')=E_{\rm B}(r')/E_{\rm A}(r')=C_{\rm B}/C_{\rm A}$  (4)

where r' is an unique equivalent radius of the segment.

The detectors receive  $\gamma$ -rays from adjacent segments at a certain vertical position, as a result of geometrical configuration of object and detector. If the drum is divided into *n* vertical segments, the activity of each segment can be expressed with vector.

 $I = (I_1, I_2, I_3, ..., I_n)^T$ , and counting rate of Detector A can be expressed by  $C = (C - C - C - C)^T$ 

The relationship of 
$$I$$
 and  $C_A$  is a transfer matrix of  $EA$ .

$$\begin{cases} CA_1 = \alpha (EA_{11}I_{A1} + EA_{12}I_{A2} + \dots + EA_{1n}I_{An}) \\ CA_2 = \alpha (EA_{21}I_{A1} + EA_{22}I_{A2} + \dots + EA_{2n}I_{An}) \\ \vdots \\ CA_n = \alpha (EA_{n1}I_{A1} + EA_{n2}I_{A2} + \dots + EA_{nn}I_{An}) \end{cases}$$
(5)

where the  $EA_{ij}$  is the contribution of the  $j^{\text{th}}$  segment to  $i^{\text{th}}$  vertical position, and depends on the detection efficiency, the geometry and absorption material in the drum;  $\alpha I_{Ai}EA_{ii}$  is counting rate from the  $i^{\text{th}}$  segment recorded at the  $i^{\text{th}}$  vertical position by Detector A.

Similarly, counting rate of Detector B can be expressed by Eq.(6),

$$\begin{cases} C_{B1} = \alpha (EB_{11}I_{B1} + EB_{12}I_{B2} + \dots + EB_{1n}I_{Bn}) \\ C_{B2} = \alpha (EB_{21}I_{B1} + EB_{22}I_{B2} + \dots + EB_{2n}I_{Bn}) \\ \vdots \\ C_{Bn} = \alpha (EB_{n1}I_{B1} + EB_{n2}I_{B2} + \dots + EB_{nn}I_{Bn}) \end{cases}$$
(6)

where,  $\alpha I_{Bi}EB_{ii}$  is counting rate of the *i*<sup>th</sup> segment

recorded at the  $i^{th}$  vertical position by Detector B.

Then, equivalent radius of the  $i^{\text{th}}$  segment,  $r_i'$ , can be determined from Eq.(7).

$$F(r_i') = \frac{E_{\rm B}(r_i')}{E_{\rm A}(r_i')} = \frac{I_{\rm Bi}EB_{ii}}{I_{\rm Ai}EA_{ii}}$$
(7)

The  $EA_{1i}$ ,  $EA_{2i}$ ,...,  $EA_{ni}$ , and  $EB_{1i}$ ,  $EB_{2i}$ ,...,  $EB_{ni}$ , can be calculated with the  $r_i'$ , and new transfer matrices of *EA* and *EB* can be established.

The ISGS is performed as follows. The initial  $EA^1$  and  $EB^1$  are calculated by assuming uniform matrix and activity, and  $I_{A1}$  and  $I_{B1}$  are obtained by Eqs.(5) and (6). Using k=1 as loop index starting,  $F(r_i')^{(k+1)}$  (i = 1, 2, 3, ..., n) is calculated by Eq.(7) using  $EA^k$ ,  $EB^k$ ,  $I_A^k$  and  $I_B^k$ . The new transfer matrices ( $EA^{k+1}$  and  $EB^{k+1}$ ) are calculated by determining  $r_i'^{(k+1)}$  (i = 1, 2, 3, ..., n). The  $I_A^{k+1}$  and  $I_B^{k+1}$  are obtained by solving Eqs.(5) and (6). On reaching the required number (the sum of activities), the loop ends.

## **3** Simulation model

The simulation model is given in Fig.3. The drum is a  $\Phi$ 56 cm×90 cm cylinder of 1.2-mm wall thickness. It is divided into 9 vertical segments of 10-cm height each. A well type HPGe detector of  $\Phi$ 6.2 cm×5.95 cm, wrapped by an aluminum layer of 1.5 mm thickness, is housed by a lead shield of 4-cm thickness, and positioned at 53-cm away from the drum center. The collimator hole is of 6 cm×6 cm×15 cm.



Fig.3 Schematic model of measurement system.

In order to fix Detector B at the best position, F(r) at L=10.5, 14, 17.5, 21 and 24.5 cm was simulated by MCNP code using an ideal line source (Source 1 in Fig.3) of <sup>137</sup>Cs (661.7 keV) at the same

height as one segment. The filling material in the drum was H<sub>2</sub>O because its mass attenuation coefficient is about the same as most organic materials in  $0.3 \text{ g} \cdot \text{cm}^{-3}$ density. Fig.4 shows that the F(r) can be calculated using the Ls as a function of radial source position. Because the r' is only determined at a monotone F(r), the suitable distances are L=17.5, 21, and 24.5 cm, and L=17.5-cm is the best considering the curve slope and range. Fig.5 shows that F(r) at different matrix densities at L=17.5 cm are almost monotone, i.e. the position of Detector B is irrelevant to the density.



**Fig.4** F(r) at different Detector B positions as a function of radial source position.



**Fig.5** F(r) at different densities at L=17.5 cm.

### 4 Results and discussion

In order to evaluate the ISGS, the activity was analyzed by an iterative method using Eqs.(5) and (6), and 20 loops were performed by 200 iteration number at every loop.

#### 4.1 Single source in homogenous matrix

The waste drums at nuclear power plants are not likely

to have homogenous activity and density distribution, and this causes the largest error in traditional SGS with a point source. In Fig.3, we marked three ideal single sources: (1) a line source of the same segmented height, (2) a point source at vertical center of the segment, and (3) a point source at the junction of two segments. Taking the line source with 12-cm radial position and 0.3 g·cm<sup>-3</sup> density as an example, a precise radius can be obtained in just 3 loops (Table 1).

| Loop number | <i>r'</i> / cm | Isimulated / Itrue |
|-------------|----------------|--------------------|
| 1           | _              | 1.437              |
| 2           | 11.975         | 0.998              |
| 3           | 12.002         | 1.000              |
| 4           | 12.000         | 1.000              |
| 5           | 12.000         | 1.000              |

Fig.6 is the comparison of simulation results by traditional SGS with the ISGS in ratio of activities (simulated/true) and equivalent radius, as a function of radial source position. The simulated activity by traditional SGS decreases with increasing radius at densities of 0.3 and 0.6  $g \cdot cm^{-3}$ , whereas this kind of changes is not so obvious at the density of 1.0 g  $\cdot$  cm<sup>-3</sup>, despite of the serious influences of a narrow collimator on outer source positions. It can be expected that densities higher than 1.0  $g \cdot cm^{-3}$  shall result in great influence of attenuation on collimation. This is a disadvantage of traditional SGS. Comparatively, the ISGS results are in good agreement with the true value. At the errors of less than 21%, the average ratio of simulated-to-true for the single source is 0.99, 1.00 and 1.01 at densities of 0.3, 0.6 and 1.0 g·cm<sup>-3</sup>, respectively. Fig.6 also shows that the equivalent radius is consistent with the real value at the three densities except for a small error of equivalent radius between point source and line source. The systematic errors of Sources 2 and 3 slightly increase with the radius of the point source or the matrix density, because the source height greatly impacts on the detector response when the source is close to the detector or the linear attenuation coefficient increases. This may be weakened by reducing the segmented height and the collimator hole.



**Fig.6** Comparison of the results from traditional SGS and the improved SGS in activity ratio and the equivalent radius, as a function of source position. (a and b)  $\rho$ =0.3 g·cm<sup>-3</sup> (c and d),  $\rho$ =0.6 g·cm<sup>-3</sup> (e and f),  $\rho$ =1.0 g·cm<sup>-3</sup>.

## 4.2 Multiple sources in homogenous matrix

For randomly distributed 25 sources in the drum, the average ratios of simulated-to-true activities are 0.98, 1.04 and 1.06 at densities of 0.3, 0.6 and 1.0 g·cm<sup>-3</sup>, respectively; and the relative errors are less than 7%, 14% and 16%, respectively. As shown in Fig.7, seven point sources are located at the 4–6 segmented drum for 9 segments from bottom to top. It can be seen in Table 2 that the equivalent radius can be determined by just 3–4 loops of calculation.



Fig.7 Sketch map of a multiple sources case.

| Loop number | $r_4' / cm$ | $r_5'$ / cm | $r_6'$ / cm | $I_{\rm A4}$ | I <sub>A5</sub> | $I_{A6}$ | Isimulated / Itrue |
|-------------|-------------|-------------|-------------|--------------|-----------------|----------|--------------------|
| 1           | -           | -           | -           | 0.307        | 0.733           | 0.178    | 1.217              |
| 2           | 15.714      | 12.144      | 0.000       | 0.225        | 0.758           | 0.039    | 1.023              |
| 3           | 18.788      | 11.060      | 0.000       | 0.240        | 0.723           | 0.037    | 1.000              |
| 4           | 18.705      | 11.081      | 0.000       | 0.240        | 0.724           | 0.037    | 1.001              |
| 5           | 18.699      | 11.080      | 0.000       | 0.240        | 0.724           | 0.037    | 1.001              |
| 6           | 18.700      | 11.080      | 0.000       | 0.240        | 0.724           | 0.037    | 1.001              |
| 7           | 18.700      | 11.080      | 0.000       | 0.240        | 0.724           | 0.037    | 1.001              |

**Table 2**First seven loops for a multiple sources case.

#### 4.3 Source in heterogeneous matrix

The ISGS was used to analyze a set of data obtained by a TGS system. The detector was positioned at four horizontal positions (L=3.5, 10.5, 17.5 and 24.5 cm), and the drum was rotated gradually at 15°. One segment was taken by the 4×24 discrete measurement of a heterogeneous sample (containing water, wood and air) in average density of 0.2 g·cm<sup>-3</sup>. A <sup>137</sup>Cs point source of 30080 Bq was placed in the drum at the four

positions. Note that the geometry is not exactly the same as the simulated model described above. The average counting rates of the 24 measurements at 3.5 and 17.5 cm were taken as that of the two detectors, respectively, as given in Table 3. For example, *ab* or *abc* means two or three point sources in position *a*, *b*,

and c. By comparing the equivalent radius with the real radius, the ISGS relative errors of activity are better than that of the traditional SGS, and are comparable to TGS. The larger source error in position c is may be due to that the material surrounding the source has a large average density.

 Table 3
 Point source and multiple sources at different positions in a heterogenous sample.

| Positions $C_{\rm B}/C_{\rm A}$ | $C \mid C$            | $R_{\rm true}$ / cm | <i>r'</i> / cm | Error / %        |                 |                            |  |
|---------------------------------|-----------------------|---------------------|----------------|------------------|-----------------|----------------------------|--|
|                                 | $C_{\rm B}/C_{\rm A}$ |                     |                | The improved SGS | Traditional SGS | Tomographic gamma scanning |  |
| а                               | 0.00                  | 0                   | 0              | -6.89            | 70.93           | -5.62                      |  |
| b                               | 0.16                  | 10                  | 8.08           | -3.62            | 40.68           | 0.41                       |  |
| с                               | 0.78                  | 20                  | 17.45          | 0.68             | -6.48           | 1.72                       |  |
| d                               | 0.51                  | 14                  | 13.96          | -17.37           | -8.50           | -6.72                      |  |
| ab                              | 0.07                  | _                   | 4.85           | -4.24            | 55.81           | -2.61                      |  |
| bc                              | 0.41                  | _                   | 12.7           | -0.94            | 17.10           | 1.07                       |  |
| cd                              | 0.65                  | _                   | 15.88          | -7.71            | -7.49           | -2.50                      |  |
| abc                             | 0.24                  | _                   | 9.75           | -0.84            | 35.04           | -1.16                      |  |
| bcd                             | 0.44                  | _                   | 12.97          | -6.87            | 8.57            | -1.53                      |  |
| abcd                            | 0.29                  | _                   | 10.8           | -4.36            | 24.16           | -2.55                      |  |

The results show that all cases satisfy with the ISGS system. Because the counting rates recorded by the detectors are sensitive to the system geometry, the optimum drum-to-detector distance, height and depth of collimator need be further calculated.

## 5 Conclusions

In summary, two identical detectors were used as determining the approximate radial position of radioactive sources to improve the traditional SGS, excluding the assumption of homogenous distribution of the radioactive sources. This may be used for SGS device with small modified software and radioactive waste drums assaying.

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