ESTIMATION OF SYSTEMATIC ERROR OF THE GAMMA TOMOGRAPHY FOR CORRECTION OF SELF-ATTENUATION IN ASSAY OF RADIOACTIVE WASTE

TRAN QUOC DUNG*

ABSTRACT

Based on simulating measurement system to assay radioactive waste drums a model for estimation of the lump effect, especially for plutonium, in the tomography technique is given. The calculation results demonstrated that the tomography technique can successfully be used for measuring the heterogeneous waste drums containing lumps. In the cases considered, the dimensions of a pixel are chosen equal to 1cm the errors for the lump of plutonium metal are about 25 %. Some results for the various shapes of lump are given.

Keywords: gamma techniques, radioactive waste, gamma tomography, self-attenuation.

TÓM TẮT

Đánh giá sai số hệ thống của kĩ thuật chụp ảnh cắt lớp cho việc hiệu chỉnh sự tự hấp thụ trong việc kiểm tra chất thải phóng xạ

Dựa trên việc mô phỏng hệ thống kĩ thuật chụp ảnh cắt lớp để kiểm tra chất thải phóng xạ, một mô hình tính toán đã được đưa ra nhằm đánh giá sai số hệ thống gây bởi hiệu ứng tự hấp thụ, đặc biệt là của kim loại plu-tô-ni. Các kết quả tính toán cho thấy rằng kĩ thuật chụp ảnh cắt lớp có thể sử dụng để kiểm tra các thùng chứa chất thải phóng xạ không đồng nhất. Trong các trường hợp đã được xem xét, khi kích thước của ô mạng được chọn là 1cm thì sai số khoảng 25% đối với nguồn là kim loại plu-tô-ni. Một số kết quả cho các nguồn có dạng hình học khác nhau cũng được đưa ra.

Từ khóa: kĩ thuật gamma, chất thải phóng xạ, chụp ảnh cắt lớp gam-ma, tự suy giảm.

1. Introduction

The fuel cycle process results in a considerable amount of radioactive waste which is usually stored in sealed drums. Safeguards and waste management require non-destructive techniques to assay the radioactive content of waste for accounting and disposal purposes. Gamma techniques are the most widely used because of their characteristics. They can be used to determine directly the content of particular isotopes. For practical application, gamma ray counting systems are usually simpler and easier than other techniques. The gamma measurement techniques are of low cost. The Segmented Gamma Scanner (SGS) is a traditional technique that has been used for almost practical cases [1,2]. However, the accuracy depends on many factors: non-uniform distribution of radioactive source within the drum; inhomogeneous distribution

* PhD., Centre for Nuclear Techniques in Ho Chi Minh City

of non-radioactive materials [3,4,5]; the lump effect, specially for uranium and plutonium assay [2,6]; the drum-to-detector distance [5].

In order to increase the accuracy some recent methods were proposed: technique using two identical detectors [7,8]; technique utilising multichannel scaling to identify inhomogeneity and to correct results of SGS [4]; technique of measuring a drum with different geometry and/or some different gamma energy lines of the isotope of interest [9,10,15]; gamma tomography techniques [11,12]; gamma technique for the assay of radioactive waste drums using two measurements from opposing directions [16, 17]. Each technique has its advantage and disadvantage. Choosing a measuring technique depends on the situation involved.

Several experiments and calculations show that particle size of nuclear materials having significant self-attenuation (lump effect) can cause very large errors [2,13,14]. This problem still exists, although various methods, including neutron and gamma techniques, are being studied to compensate this effect. Passive and active computed tomography is being considered as a mean for solving this problem [6,14]. However, some effects from factors such as size of pixel and lump, matrix, position of lump in a pixel to the results in this technique have not been considered. This paper presents a model based on simulating measurement system for estimation of these factors, especially for plutonium. The results of the calculation demonstrated that tomography technique can be successfully used for measuring the heterogeneous waste drums containing lumps. When the size of a pixel is chosen equal to 1cm the errors are about 25 % for lumps of plutonium metal. Some results for the various shapes of lump are also given.

2. Model for evaluation of errors

In the tomography technique, an image may be approximated by several square cells called image elements or pixels. There are two parameters estimated within a pixel, the linear attenuation coefficient and the radioactive concentration. The parameters within a pixel are assumed to be constant; each of them is in fact its average value within a pixel. Therefore, in order to simplify the calculation but not to lose the generality a single source in a pixel is investigated here.

Supposing a lump of radioactive source in a pixel is considered as in Fig. 1, and the lump is divided into such n of small elements that the self-absorption in the element can be ignored.

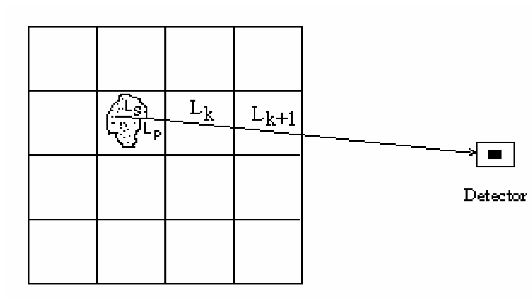


Figure 1. *The lump considered in a pixel*

Then, the count rate of detector caused by the i-th element of the source can be given as

$$C_i = \alpha \cdot \beta_i \cdot A_i \cdot \frac{\exp[-(\mu_p \cdot L_p^i + \mu_s \cdot L_s^i)]}{H_i^2} \quad (1)$$

Where

α- a function of yield of gamma line of isotope, the gamma ray energy and characteristic of the detector.

β_i - a function representing the absorption by the neighbour pixels in the path from the considered pixel to the detector. If μ_k, L_k are called as the linear absorption coefficient, and the path length in the k-th neighbour pixel, respectively. In principle of the tomography technique, μ_k are determined. L_k can be calculated after the sample-to-detector distance (K) is known. Therefore, β_i can be given as $\beta_i = \exp(-\sum_k \mu_k \cdot L_k)$

H_i – the distance from the i-th element of the source to the detector.

A_i - activity of i-th element. If A is defined as the total activity of source; μ_s, μ_p, L^i_s, L^i_p are the linear absorption coefficients, and the path lengths of gamma rays in the lump and matrix of the pixel, respectively.

So, the count rate of detector caused by whole source can be presented as

$$C = \alpha \cdot \frac{A}{n} \cdot \sum_{i=1}^{n} \beta_i \cdot \frac{\exp[-(\mu_p \cdot L_p^i + \mu_s \cdot L_s^i)]}{H_i^2} \quad (2)$$

In principle of the tomography technique, count rate of the detector caused by the considered pixel is determined as

$$C = \alpha \cdot \frac{A_t}{m} \cdot \sum_{i=1}^{m} \beta_i \cdot \frac{\exp(-\mu \cdot L^i)}{H_i^2} \quad (3)$$

Similarly above, here, supposing the pixel is divided into such *m* of small elements that the self-absorption in the element can be ignored. A_t- measured value of activity. μ, L^i - linear absorption coefficient and, path length of gamma ray in the pixel, respectively.

In order to simplify the problem without losing the generality here α, β_i and the total content A of source are assumed equal to 1. The square lumps of metal plutonium are assumed. The following parameters are chosen: gamma line of 414 keV, then μ_p is 2.6 cm^{-1}; size of lump is in the range 0.05-5 cm; dimensions of the pixel is 1-5 cm; density of matrices is 0.3, 0.8, 1.2 g/cm^3. K is assumed to be equal to 20 and 50 cm. The different positions of the lump are considered as in four corners within the square pixel.

The numerical value of expressions (1) and (2) are approximately calculated with errors smaller than 0.01%.

3. Results and discussion

Based on the above mathematical simulation, effects of the following parameters on the error have been estimated: size of the lump; position of the lump in the pixel; shape of the lump; size of the pixel; the density of matrices.

Several simulations have been made, and some results are given here. The dependence of some typical relative errors (A_t/A) on size of lump, size of pixel is illustrated in Fig. 2. This investigation demonstrates that the error strongly depends on the ratio of size of lump to the size of pixel. The maximum errors can be obtained when this ratio is in the range 0.3-0.5. The size of the pixel affects fairly on the measurement results. The maximum error increases from -27% to -71% corresponding to size of pixel of 1 and 5 cm, respectively. The absorption of matrix has the effect on the result as shown in Fig. 3. The larger the ratio of size of lump to size of pixel, the stronger this effect. However the errors are not larger than 20% if the size of pixel is equal to 1cm.

Position of the lump also has the effect on the results. Figure 4 illustrates errors caused by position, size of lump and pixel. When the source is close to the detector, the path length (L_m) of gamma rays from the source to detector distance decreases.

Therefore, count rate of the detector increases that results in large ratio of A_t/A. It is evident that the shorter the source to detector distance, the larger the ratio of A_t/A. However this change is quite small when size of pixel equal to 1 cm. For example, for position 1 and 3 the ratio of A_t/A changes from 0.85 to 1.05 only while it changes from 0.55 to 1.55 for size of pixel 5 cm, respectively.

The difference between the ratio of A_t/A of positions 1 and that of positions 2 is small if K is larger than 20cm. This also happens for positions 3 and 4.

The dependence of error (A_t/A) on distance from pixel to detector, on size of the lump and the pixel is displayed in Fig. 5. Although distance from pixel to detector is changed in the large range of 20-50 cm, the variation of error is small, and it can be ignored in the case of size of pixel of 1cm. This has a meaning that errors caused by position of pixel are inconsiderable.

The above results are given for the square lumps only. In practice the lumps have various shapes. However they can be supposed as a set of square elements, and they can be investigated by the above calculation model. The results of some typical cases are illustrated in Fig.6.

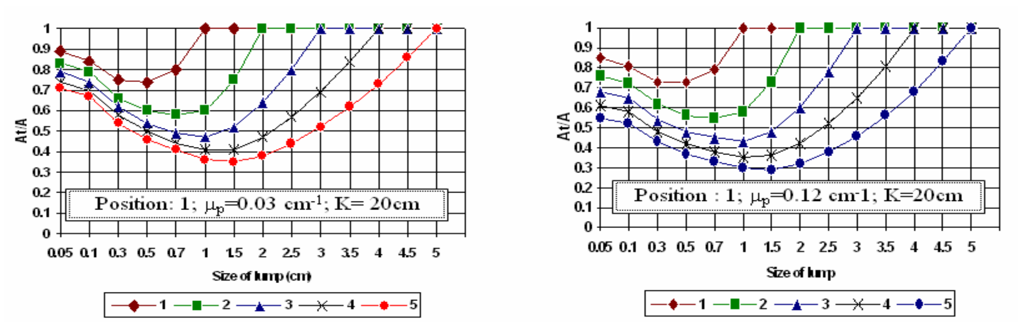
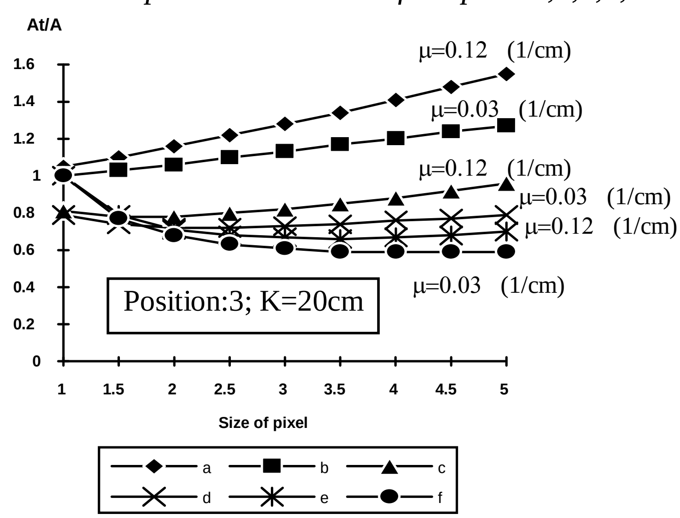


Figure 2. *Effect of size of lump, size of pixel on the error. Note: the curves 1,2,3,4,5 correspond with the size of the pixel 1,2,3,4, and 5 cm, respectively*



a) Size of lump: 0.05 cm
b) Size of lump: 0.05 cm
c) Size of lump: 0.5 cm
d) Size of lump: 0.5 cm
e) Size of lump: 1.0 cm
f) Size of lump: 1.0 cm;

Figure 3. *Effect of size of lump and matrix on the results*

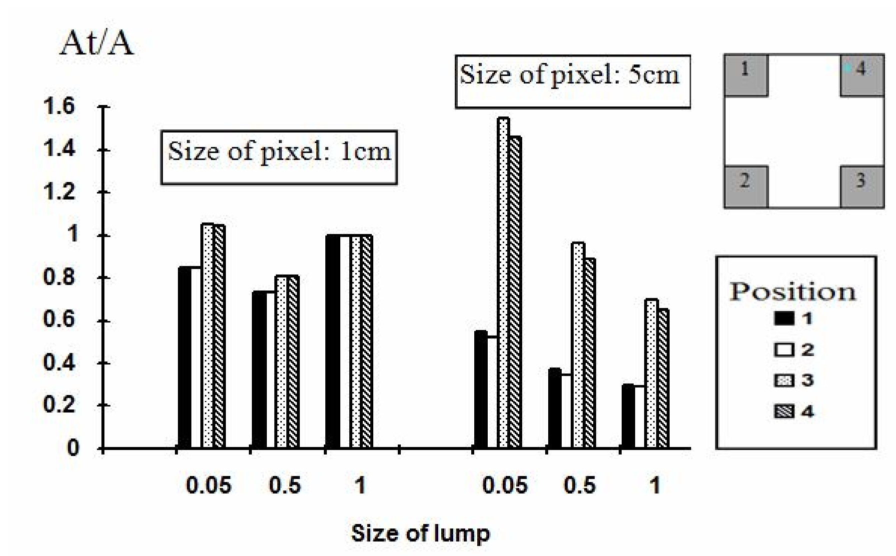


Figure 4. *Effect of position of the lump on the results, here four diferent positions (1,2,3 and 4) of the lump within the pixel are also considered (Note: μ_m=0.12 cm^{-1}; K=20cm)*

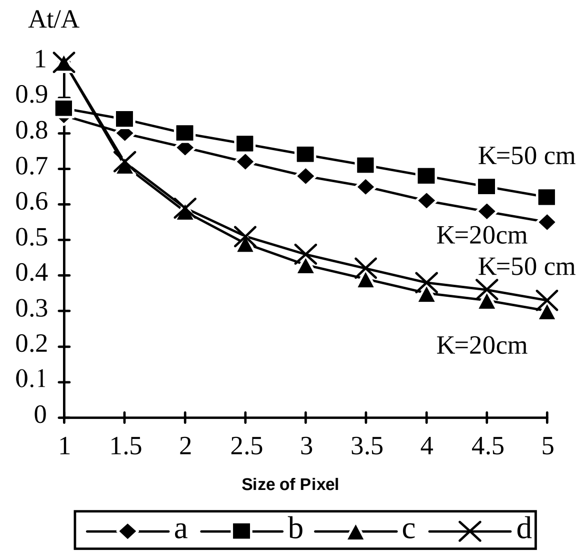


Figure 5. *The dependence of error (A_t/A) on pixel-to-detector distance and size of the pixel Note: μ_m=0.12 cm^{-1}; Position of lump: 1. a) and b): size of lump: 0.05 cm; c) and d): size of lump: 1 cm.*

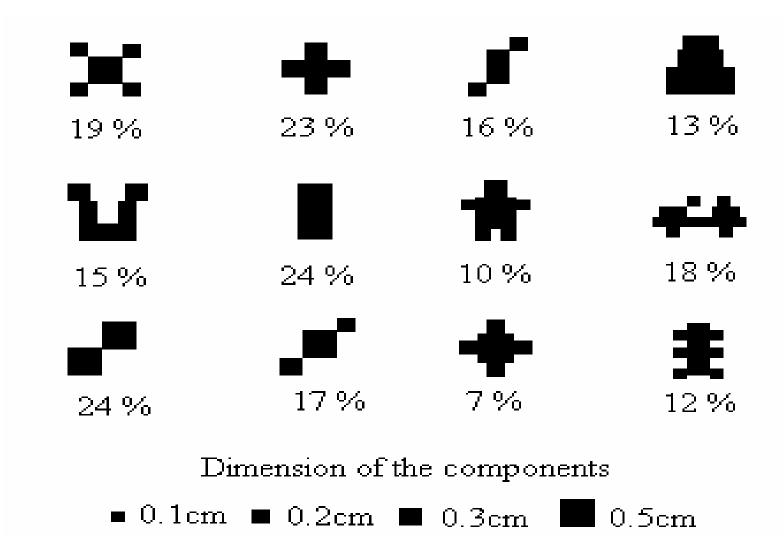


Figure 6. *Some shapes of lump and the errors are estimated*

(Note: size of pixel: 1cm; attenuation of matrix: 0.12 cm^{-1})

4. Conclusion

In the view of systematic error, tomography techniques can successfully solve the problem both of assay of heterogeneous waste drums and correction to lump. When the size of pixel is chosen equal to 1cm the errors are not larger than 25 % for lump of plutonium metal. However, in order to reduce measuring time choosing the size of pixel depends on each concrete situation.

REFERENCES

1. Augustson R.H, Reilly T.D (1974), "Fundamentals of Passive Non destructive Assay of Fissionable Material", *LA-5651-59*.
2. Bjork C.W (1987), "Current Segmented Gamma Scanner Technology", *Proceeding of. 3rd International Conference on Facility Operation Safeguards Interface*, San-Diego, California, 1987.
3. Cesana A, Terrani M and Sandrelli G (1993), "Gamma Activity Determination in Waste Drums from Nuclear Plants", *Applied Radiation and Isotopes.*Vol 44, No. 3, pp. 517.
4. Estep R. J (1990), "Assay of Heterogeneous Radioactive Waste by Low-Resolution Tomographic Gamma Scanning", *Transactions of the American Nuclear Society*, 62, pp. 178.
5. Estep R. J, Prettyman T.H and Sheppard G.A (1994), "Tomographic gamma scanning to assay heterogeneous radioactive waste", *Nulcear Science and. Engineering*, Vol.118, pp.145.
6. Gillespie B. M (1994), "Inhomogeinetiy Detection and Correction in Drum Waste Assay Systems", *Proceedings. of IAEA Symposium. on International Safeguards*, Vienna.
7. Levai. F, Z. Nagy, Tran Quoc Dung (1995), "Low Resolution Combined Emission-Transmission Imaging Techniques for Matrix Characterization and Assay of Waste", *Proceedings of the 22nd ESARDA Meeting and Seminar on Safeguards and Nuclear* Material Management, Aachen, Germany. , 9-11 May.
8. Martz H.E, Roberson G.P, Camp D.C, Decman D.J, Jackson J.A and Becker G.K (1998), "Active and Passive Computed Tomography Mixed Waste Focus Area Final Report", *Lawrence Livermore National Laboratory, UCRL-ID-131695*.

9. Prettyman T.H, Foster L.A and Estep R.J (1996), "Detection and measurment of gamma-ray self-attenuation in plutonium residues", *Los Alamos National Laboratory, LA-UR-96-2620*.

10. Sprinkle J. K and Hsue S. T (1987), "Recent Advantage in Segmented Gamma Scanner Analysis", Proc. 3rd *Proceeding of. 3rd International Conference on Facility Operation Safeguards Interface* San Diego, California.

11. Tran Quoc Dung (1997), "Calculation of the systematic error and correction factors in gamma waste assay system", *Annals of Nuclear Energy,* Vol. 24, No 1, pp. 33.

12. Tran Quoc Dung (1997), "Modification to the technique using two detectors for assay of radioactive material in waste drums", *Annals of Nuclear Energy,* Vol. 24, No 8, pp. 645.

13. Tran Quoc Dung (1998), "New measuring technique for assay of radioactive material in waste drums", *Progress in Nuclear Energy,* Vol. 33, No. 4, pp. 403.

14. Tran Quoc Dung (1998), "Some theoretical results of gamma techniques for measuring large samples", *Nuclear Instruments and Methods- A.*Vol. 416, pp. 505.

15. Trần Quốc Dũng (2004), "Improvement of the Segmented Gamma Scanner for assay of radioactive waste", *Proceeding of the 9 th Asia Pacific Physics Conference,* Hanoi, 25-31 November.

16. Tran Quoc Dung, Nguyen Duc Thanh, Luu Anh Tuyen, Lo Thai Son, Phan Trong Phuc (2009), "Evaluation of a gamma technique for the assay of radioactive waste drums using two measurements from opposing directions", *Applied Radiation and Isotopes*, Vol.67, Iss. 1.

17. Tran Quoc Dung (2010), "A simple gamma technique for the assay of radioactive waste drums", *International Journal of Nuclear Energy Science and Technology,* Vol. 5, No. 4.

(*Received: 11/01/2013; Revised: 27/5/2013; Accepted: 21/6/2013)*