APPLICATION OF HIGH-PENETRATING INTROSCOPY SYSTEMS FOR RECOGNITION OF MATERIALS

S.A. Ogorodnikov, V.I. Petrunin, M.F. Vorogushin, NPK LUTS NIIEFA, St. Petersburg, Russia

Abstract

The paper shows possibility of usage of high-penetrating introscopy systems operating in dual energy mode in 4-10 MeV energy range for recognition of groups of materials according to their atomic number. The recognition method itself, its effectiveness and limits of applicability are discussed. The results of recognition processing of interlaced images scanned out in dual energy mode are presented. Some improvement tools of the method and possibility of its implementation in customs inspection systems for vehicles and large-scale containers are briefly discussed.

1 INTRODUCTION

The well-known dual energy method of material discrimination is widely used in X-ray inspection systems for security control of hand luggage in customs and other security checkpoints [1]. Its major advantage in comparison with the common single energy X-ray installations is possibility of determination (or at least an approximation) of material's mass absorption coefficient and effective Z number. X-ray transmission data of inspected object are obtained for both energies, computer processed and resulted image is displayed on a monitor in special palette for visual identification of contraband or hazardous materials. Special computer software identifies various materials and artificial colors are assigned to various values of Z. Typical energy range for such installations is below 0.5 MeV and stipulated by strong dependence of gamma attenuation coefficient from Z due to prevailing of photoelectric interaction (σ_τ~Z^5). Application of dual energy method for X-ray systems with high penetration ability (energy up to 10 MeV) intended for inspection of vehicles and large-scale containers encounters physical obstacles as far as 1<E<10MeV is energy range of domination of Compton effect with its weak dependence of attenuation coefficient: μ_c~Z/A. The purpose of this paper is to show the applicability of dual energy method in 4÷10 MeV range for recognition of groups of materials according to their effective atomic number.

2 METHOD

The physical principle of dual energy method is based on the fact that due to the exponential law of monochromatic gamma radiation attenuation the ratio of logarithmic transparencies at nominal and dual energy characterizes material of the barrier irrespective to its thickness. For the case of continuous spectrum of bremsstrahlung the material discrimination task for two energies of electron beam E_{ac1},E_{ac2} can be expressed in mathematical terms as solution of the system of two non-linear integral equations for experimentally measured high and low energy transparencies T_{1exp}, T_{2exp} of a barrier with respect to its effective atomic number Z and thickness t:

$$\begin{cases} T_{1\exp} = T(E_{ac1},t,Z) = \dfrac{\int_0^{Eac1} \frac{dP}{dE_\gamma}(E_{ac1},E_\gamma)\cdot e^{-\mu(E\gamma,Z)t}\cdot dE_\gamma}{\int_0^{Eac1} \frac{dP}{dE_\gamma}(E_{ac1},E_\gamma)\cdot dE_\gamma} \\ T_{2\exp} = T(E_{ac2},t,Z) = \dfrac{\int_0^{Eac2} \frac{dP}{dE_\gamma}(E_{ac2},E_\gamma)\cdot e^{-\mu(E\gamma,Z)t}\cdot dE_\gamma}{\int_0^{Eac2} \frac{dP}{dE_\gamma}(E_{ac2},E_\gamma)\cdot dE_\gamma} \end{cases} \quad (1)$$

where energy distribution proportional to detector response is product of spectral distribution of bremsstrahlung intensity according to Schiff's formula and detector response factor:

$$\frac{dP}{dE_\gamma}(E_{ac},E_\gamma) = \frac{dI}{dE_\gamma}(E_{ac},E_\gamma)\cdot\left(1-e^{-\mu_{\det}(E\gamma)\cdot t_{\det}}\right)\cdot\frac{\mu_{\det}^{en}(E_\gamma)}{\mu_{\det}(E_\gamma)} \quad (2)$$

As it has been shown [2], except for the group of heavy metals at some t values, the system (1) has unique solution for all materials for the practically used thickness range. In order to get rid of the ambiguity, certain measures have to be applied, for example, spectral filtering of primary bremsstrahlung. Due to the low sensitivity of the method for the given energy range, practically discrimination can be performed only for the limited number of groups of materials.

3 EXPERIMENTS

In order to verify the applicability of the material recognition method for the customs purposes a series of experiments were carried out at the full scale laboratory installation of NPK LUTS NIIEFA imitating inspection system equipped with:

- industrial linear electron accelerator UELV-10-2D-40 on traveling wave with energy at the nominal mode 8MeV and at dual one 4MeV; pulse duration – 5 μsec; repetition rate – 100 Hz; the accelerator operated at so called interlaced mode: each even pulse generates high energy and each odd – low;
- Collimating system of bremsstrahlung beam consisting of primary and second collimators; narrowed fan-like beam scanning in vertical plane;

- Detector line consisting of 640 channels of detection; sensitive elements: p-i-n diodes in combination with scintillation crystals;
- Transportation system of tested samples across the radiation beam.

The procedure of data processing and image visualization included the following steps:

1. Raw data interlaced file was decomposed into high and low energy image files;
2. Data counts were converted into transparencies by means of special non-linear correction procedure;
3. Third auxiliary enhanced image, was obtained through deconvolution of high energy image with experimentally measured Point Spread Function of the system;
4. Special bilateral filtration of both primary high and low energy images was fulfilled with experimentally selected domain and range corns;
5. Material recognition procedure was performed for each pixel by means of processing of experimental logarithmic transparencies; thickness and effective atomic number were calculated according to (1);
6. Color's hue for each pixel on image was evaluated from Z-number according to table 1; color's saturation varied from maximum for region with best discrimination ($15gr/cm^2<t<120gr/cm^2$) to minimum for poor discrimination regions in vicinity of white field (absorption of air) and higher absorption region (penetration limit of low energy bremsstrahlung); luminosity of pixel's color was evaluated from corresponding value of transparency taken from the third deconvolved image; color of each pixel was combined from calculated hue, saturation and luminosity values; the output image was visualized.

Experiments were performed for a set of wedge-like tested samples with different atomic numbers and also for a large-scale transport container containing materials of all four Z-groups (table 1). Colorized images demonstrate effectiveness of recognition method (figures 2, 3; colored representation only in electronic version of paper).

Due to the low sensitivity of method in given energy range the atomic number precision totaled ~10 for thicknesses $15gr/cm^2<t<120gr/cm^2$ (figure 1) and reached 2 in some experiments (discrimination of water and petrol [3]).

Table 1: Frame points for Material-to-Color conversion

Media	Reper material	Z	Hue
Organic	Hydrocarbon (CH_2)	~5	Red
Organic-inorganic	Silicon (Si)	14	Green
Inorganic	Iron (Fe)	26	Blue
Heavy metals	Lead (Pb)	82	Lilac

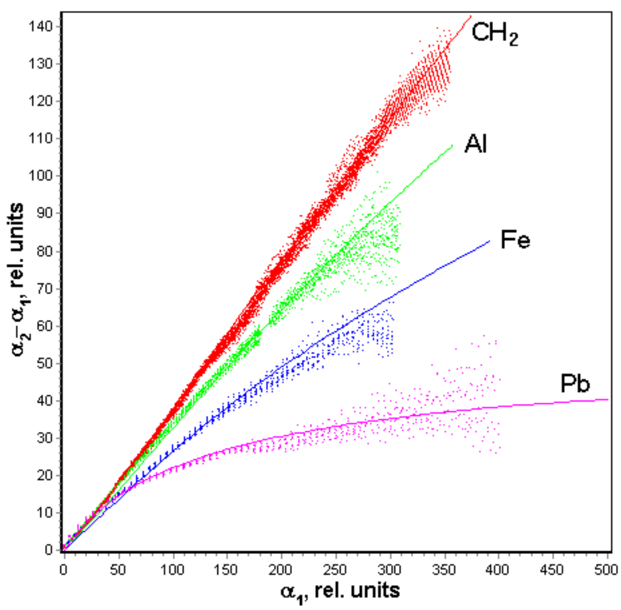

Figure 1: Calculated absorption curves for thickness 0-$120gr/cm^2$ ($\alpha_{1,2}$- absorptions for $E_{1,2}$) and spreads of experimental data of 110cm water, 35cm duralumin, 13cm steel and 9cm lead wedge samples (figure 2).

Figure 2: Recognition of tested samples (from left to right): 110cm wedge-like tank with water, 200cm wooden wedge, 35cm aluminum wedge, Plexiglas samples, lead sample, 15cm steel wedge, three 50cm plastic wedges, 4.5cm tungsten wedge, 9cm lead wedge, 5cm steel plate. Color encoding is according to table 1 (colored representation available in electronic version of the paper only).

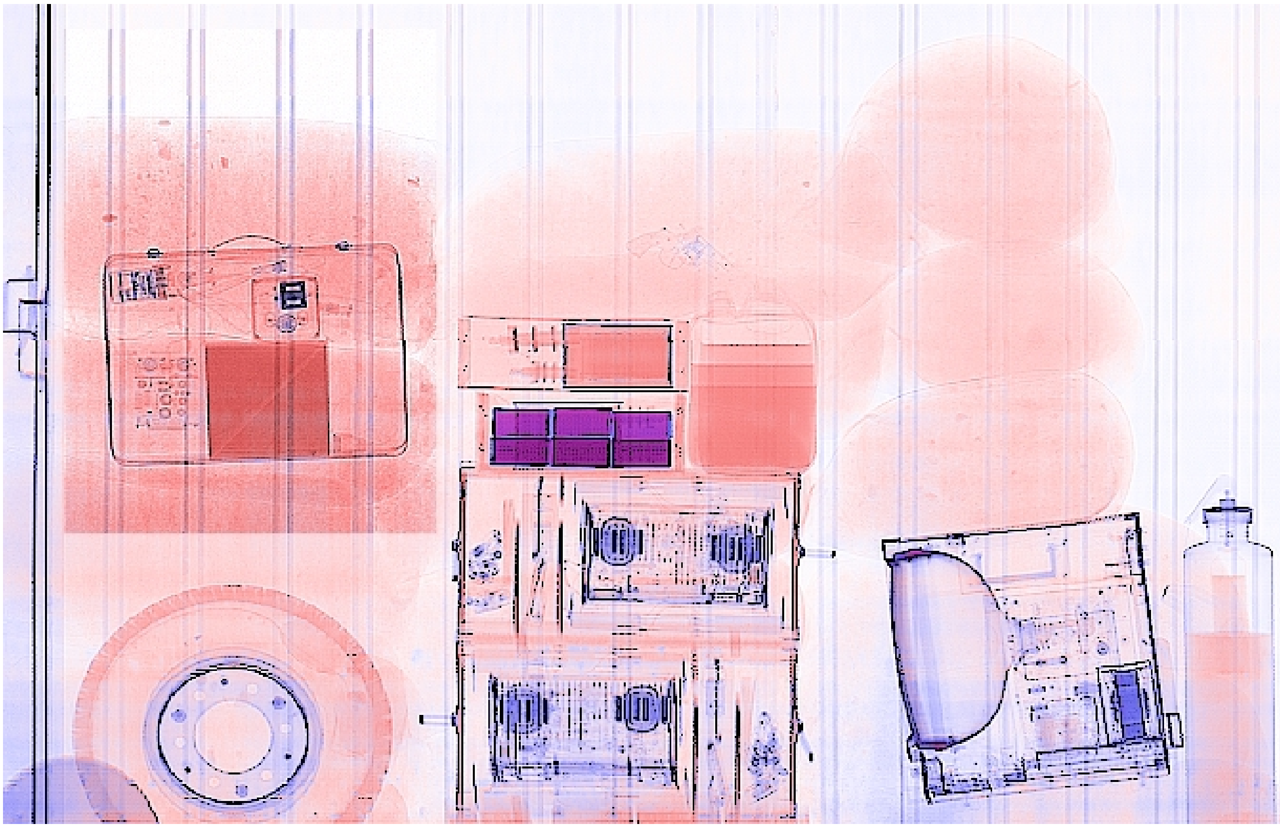

Figure 3: Image of container in TZ-palette: organic – red, inorganic – blue, heavy metals – lilac (colored representation available in electronic version of the paper only).

4 CONCLUSION

The complex of aforementioned methods allowed to overcome low sensitivity – the major obstacle for application of dual energy bremsstrahlung beams in 4-10MeV energy range for discrimination of groups of materials according to their atomic number. In $0\div120gr/cm^2$ thickness range the best results were obtained for three groups of materials: organic, inorganic and heavy metals. In order to realize the material recognition option in a real-scale customs inspection system for vehicles and large-scale containers, such system has to satisfy the following requirements:

- High energy stability of accelerator for the both levels;
- In order to eliminate spatial shift between high and low energy pulses during scanning of moving object, synchronization of both pulses must comply with the asymmetric scheme;
- Accuracy of transparencies measurement must be sufficient in order to ensure the third significant digit at both levels, therefore the number of bits of ADC must equals at least 16 and ratio of dose powers at the high level to the low one should not exceed 5;
- The theory is based on narrow gamma beam approach and, therefore, the beam path must be formed by well-aligned collimating system made of three units at least;
- Discrimination ambiguity at small thickness of the material requires initial spectral filtration of bremsstrahlung;
- For the correct transparency evaluation and suppressing of image's stripes the system must be provided with a device for non-linear correction of detectors response;
- In order to increase signal to noise ratio temporal averaging might be applied;
- Speed of data processing system should be sufficient to fulfill the necessary processing of large data volumes in real-time mode.

REFERENCES

[1] D.W.Hannum, J.E.Parmeter, "Survey of commercially available explosives detection technologies and equipment", Sandia National Laboratories, 1998.

[2] V.L. Novikov, S.A. Ogorodnikov, V.I. Petrunin, "Dual energy method of material recognition in high energy introscopy systems", Proc. 16th International Workshop on charged particle linear accelerators, 1999, Alushta, Crimea, Ukraine, appeared in ISSN 1562-6016, Problems of atomic science and technology, 1999,v.4, 93.

[3] S.A. Ogorodnikov, V.I. Petrunin, "Experiments on recognition of liquids by dual energy bremsstrahlung in 4-10MeV range", NPK LUTS NIIEFA internal report, not published.