MULTI-ENERGY RADIOGRAPHY FOR NON-DESTRUCTIVE TESTING ON THE BASE OF SCINTILLATION CRYSTAL DETECTORS

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Abstract: One of the main technical solutions used in multi-energy radiography is conversion of the penetrating X-ray radiation by a detector with its subsequent amplification and digitalization of the signal.

We used detector arrays of types "scintillator-photodiode" (S-PD) and scintillator-photoreceiving device (PRD).

In non-destructive testing systems using S-PD arrays it is possible to use scintillators of different atomic number and density, which allows functioning in the energy range from 20 keV to 10 MeV, i.e., steel equivalent thickness is from 100 µm to 300 mm.

For different objects and different purposes, different types of detector arrays and methods of control can be recommended.

Results of experimental studies of detector arrays S-PD and S-PRD used for X-ray digital radiography have shown that there exist further possibilities to increase spatial resolution of this system up to 2-3 line pairs per mm.

Theoretical analysis and experimental estimates show that the two-energy detection method not only allows one to detect organics on the background of metal, but also substantially increases (by 3-5 times) the detection ability of the system.

Introduction: X-ray digital radiography is a rapidly expanding and one of the most important methods of modern non-destructive testing [1]. In this method, alongside with the use of luminescent screens with subsequent transformation of the image onto CCD-matrix, one of the main technical solutions is conversion of the penetrating X-ray radiation by the detector array of 'scintillator-photodiode" (S-PD) type with its subsequent amplification and digitalization of the signal.

Advantages of CCD devices are instant imaging of all the object and high spatial resolution (3-5 line pairs per mm). Their disadvantage is a limited energy range, consequently, limited steel thickness of the inspected object, as well as higher costs, as compared with S-PD arrays.

In non-destructive testing systems using S-PD arrays it is possible to use scintillators of different atomic number, density and element length , which allows working in the energy range from 20 keV to 10 MeV, i.e., steel equivalent thickness is from 100 µm to 300 mm. The use of two-energy detection systems solves the problem of distinguishing between substances of similar density, but different effective atomic numbers. Both these qualities are not attainable for CCD-matrix.

Our task in developing this method consisted in the maximum use of its advantages. Specifically, we aimed at increased sensitivity and detecting ability due to optimization of parameters of the S-PD pair and an extensive use of the features of two-energy radiography. Transition to multi-energy radiography was envisaged for detection of substances with close values of the effective atomic number. The resolution was to be increased due to modernization of the design and making smaller the detector aperture. And, finally, passing from two- to three-dimensional imaging was also essential.

The above-listed directions in the system improvement were the aims of our studies in this work.

Results: Measurements of the detector sensitivity and light output of the crystals were carried out on a testing board using X-ray sources IRI (U_a=40-200 kV, I_a=0.4-1.0 mA, W anode) and REIS (U_a=5-45 kV, I_a=5-50 µA, Ag anode), RUP-350 (U_a=300 kV, I_a=6 mA) and an optical power meter "Kvarts-01". Time characteristics were measured using a testing board designed for afterglow measurements [2].

To obtain shadow X-ray images, we used testing boards «Poliscan» (a 128-channel array of photodiode-based detectors) and «Photocell» (for 32- 64-, 128- and 1024-channel detectors based on PRD). Using the Photocell board, 60 2D images of a small object were obtained at different angles (with step 6°), from which a 3D image was reconstructed.

For detection of X-ray radiation, we used detector arrays of types S-PD and scintillator-photoreceiving device (PRD). PRD includes an array of photodiodes (32, 64, 128 and 1024 channels), amplifier and commutator mounted on one silicon crystal.

We used standard scintillation crystals CsI(Tl), $CdWO_4$ and an original scintillator ZnSe(Te) developed by STC "Institute for Single Crystals" [2]. The photodiodes used were obtained from producers CCB Ritm, SPO Bit, Ukraine, and Hamamatsu, as well as PRD from SPO Bit, Kiev, Ukraine.

In our search we used traditional for scanning introscopy experimental procedure, Fig 1.

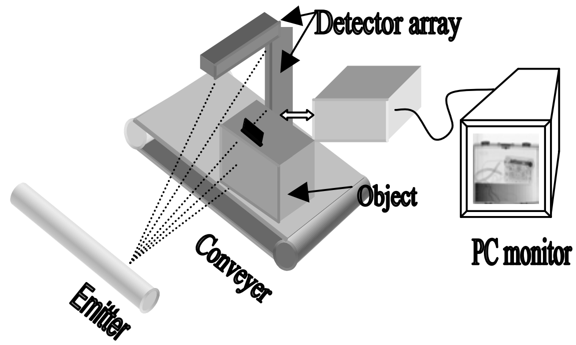


Fig. 1: Digital radiograph with detector array.

Scintillator plates of the following types were tested:

- Plates of discrete scintillation elements (DSE) – one element per channel;
- Continuous solid plates of a single crystal (SCP) – by the size of the photosensitive area of a multi-channel photoreceiver;
- Plates of dispersed scintillator (DSP) – made of tiny calibrated particles of ZnSe(Te) crystals arranged into a monolayer and optical epoxy adhesive UP4-20-3M [3].

Comparative measurements have shown (Fig.2) that serious competition to DSE plates can come only from DSP.
Interference of neighboring channels was studied for DSP prepared from ZnSe(Te) grains of different size. It is obvious that with smaller grain size the interference of neighboring channels is reduced. However, the DSP light output is also dependent upon grain size and has maximum at the grain size ~0.5 mm.
The use of laws of geometrical optics, namely, placing the inspected object much closer to the source of sharp focus than to the detector array, allows one, using DSE with step 0.8 mm, to achieve detecting abilities of 10-15 µm (Fig.3, microchip).

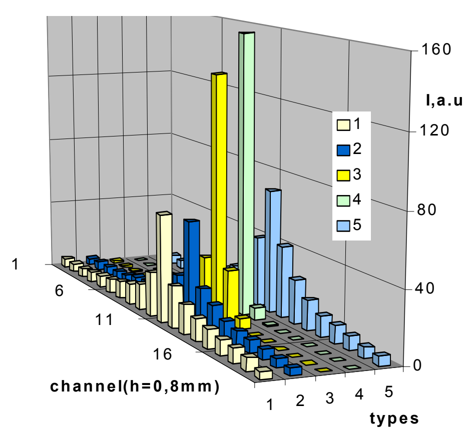
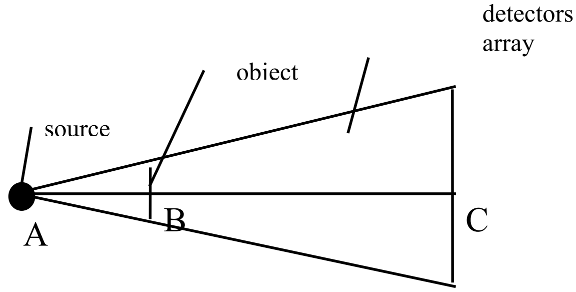


Fig. 2. Mutual interference of neighboring channels for different scintillators and types of scintillation elements: 1 - single crystal plate ZnSe(Te) with h=0,8 mm; 2 - single crystal plate ZnSe(Te) with h=0,6mm; 3-composite small-crystalline plate ZnSe(Te) (grain size 0,4 mm); 4 - individual single elements for each channel; 5 - single crystal plate CsI(Tl) with h=0,8 mm.



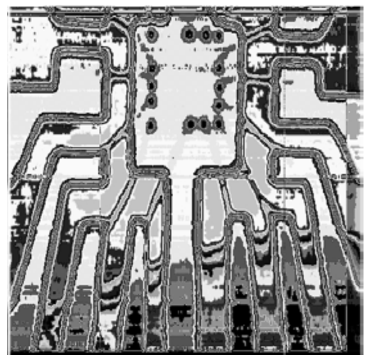


Fig.3. Experimental arrangement and microchip in plastic tank in x-ray view.

Multi-energy approach is a new promising direction in the modern digital radiography. In the most common case, it is two-energy radiography [3, 4].

As distinct from the conventional method, when the spatial structure of the object is reconstructed, in the multi-energy radiography we can reconstruct its substantional structure, effective atomic number, chemical (elemental) composition, molar concentrations of simple components, etc.

For determination of the effective atomic number and density of materials with unknown or variable composition, it is sufficient to use two-energy radiography. The effective atomic number Z_{eff} is unambiguously related to the ratio of radiographic reflexes measured at two different energies of radiation [3].

$$R = R_1 / R_2 \equiv \frac{\ln\left[V_0\left(E_1\right)/V\left(E_1\right)\right]}{\ln\left[V_0\left(E_2\right)/V\left(E_2\right)\right]} \qquad (1)$$

(V_0 and V are the signals recorded by the detectors without and with the inspected object, respectively. A universal radiographic law is assumed to be valid:

$$Z_{\mathrm{eff}} = \left[\left(aR+b\right)/\left(cR+d\right)\right]^{1/3} \qquad (2)$$

The calibration constants are determined from measurements on objects of known composition. The error in Z_{eff} determination is proportional to the contrast sensitivity of the detectors

$$S_Z = \left(\Delta Z/Z\right) \propto 2\left(\Delta d/d\right) \qquad (3)$$

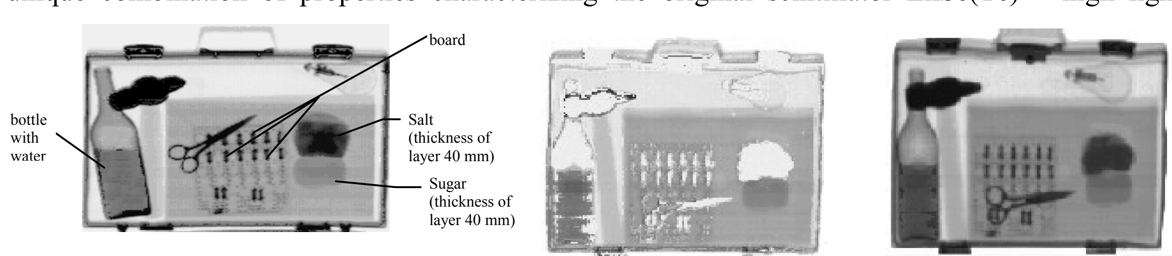
Estimates show that for introscopy systems with resolution to 4 lines/mm the effective atomic number can be reconstructed with accuracy of up to 95%. This is much better than 50% accuracy for the existing methods [3].

Discussion: Results of our studies have shown that in S-PD detectors for digital radiography the most preferable scintillators for the high energy region are CWO (0.5-10 MeV), CsI(Tl) (0.08-0.5 MeV), while in the low-energy region (20-60 keV) ZnSe(Te) is unchallenged.

Accounting for a trend in the modern digital radiography (both in the inspection and medical instruments) to use two-energy detector arrays, the combination of ZnSe(Te) and CsI(Tl)/CWO results in a new quality [5-7].

Effective atomic number *Z* of ZnSe is the same as of copper, which is usually used as a filter of the high-energy array. Therefore, if a detector with ZnSe(Te) as filter is placed before the high-energy array, this simplifies the design and improves technical characteristics of the detecting circuit as a whole [8].

A unique combination of properties characterizing the original scintillator ZnSe(Te) – high light output, fast



response, radiation stability, rather low effective atomic number together with sufficiently high density – makes this material the best among known scintillators for the low-energy detector. Combination of crystals ZnSe(Te)/CsI(Tl) in the two-energy detector array has substantially improved the sensitivity of equipment designed for detection of organic inclusions (Fig.4).

a) b) c)

Fig. 4. Object images obtained using the two-energy introscope:
a) general shadow picture of the object;
b) shadow picture with inorganic material singled out ;
c) shadow image with organic material singled out.

Using a simplified model of the two-energy detector array and spectrum of the X-ray tube with a tungsten anode (Fig.5), evaluation has been carried out of the signal ratio from high- and low-energy detectors (HED and LED) in the presence of an inspected object (which can be of different thickness and chemical composition). The other objective was to estimate reliability of the results obtained using a 12-digit ADC (noise of quantization).

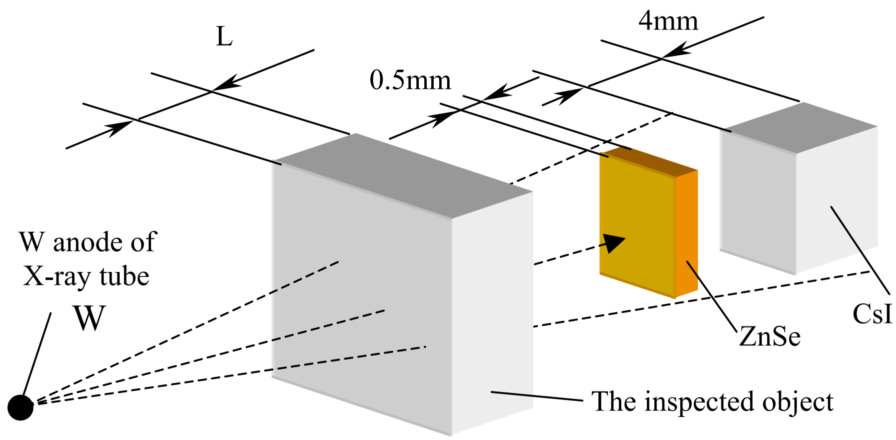


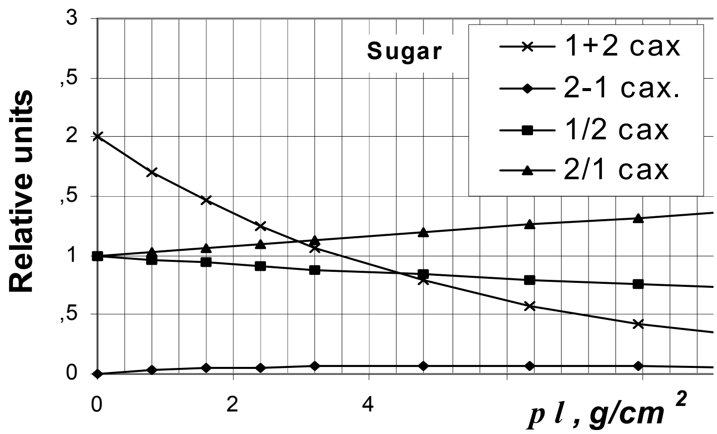
Fig. 5. A model of the two-energy detector array and spectrum of the X-ray tube with a tungsten anode.

Calculations were carried out for the following substances: Al, Cu, Fe, NaCl, H_2O, $C_{12}H_{22}O_{11}$ (sugar).

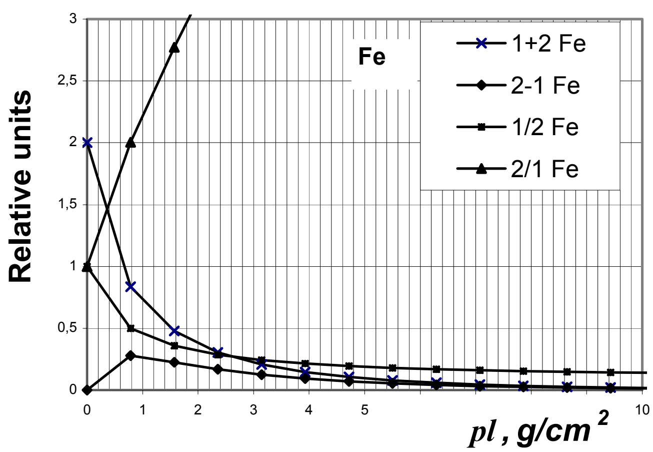
In our calculations, we used a simplified model of the two-energy detector array – each detector was replaced by a ZnSe scintillator of 0.5 mm thickness (LED) and CsI scintillator of 4 mm thickness (HED). Filtration effects of LED were accounted for. As an output detector signal, we used the calculated light flux (in relative units) formed in the scintillator under X-ray irradiation.

The calculated data were then normalized. The initial data were calculated for different thickness l of the inspected object (in cm). However, more informative is the use of parameter ρl (g/cm^2) on the x axis, where ρ is the density of the inspected object. In such presentation, the calculated plots for one and the same substance (e.g., salt as crystals and as powder – difference in density) are identical, and comparison of substances with substantially different densities becomes more obvious .To evalu(a) signals in real radiographic systems, it is convenient to show the signal sum HED+LED along the X axis.

To determine possibilities of substance identification, we have considered different values derived from the initial calculated signals (sum 1-2, difference 2-1, ratios 1 to 2 and 2 to 1 (1- LED, 2 – HED signal). These plots, (sugar) and (iron) as function of ρl (g/cm^2), are presented in Fig.6



a)



b)

Fig. 6. Ratios, differences and sum of normalized light flow for sugar (a) and iron (b) LED (1) and HED (2).

For determination of the effective atomic number of a substance, it is possible to use, as a substance characteristic, the ratio of signals HED/LED from the high-energy detector (HED) and low-energy detector (LED), accounting for the total signal (HED+LED).Fig.7a allows to assess the substance identification possibility in a real digital radiography system (DRS). Ratios 2/1 are given for different substances depending upon the signal (1-2) characterizing the fraction of X-ray radiation transmitted through the substance. Both these parameters can be easily calculated using DRS.

In using the linear amplifying circuit model, estimates of errors introduced by a 12-digit ADC show that with the total signal from two detectors less than 0.5% of the initial value, the identification errors is significantly increased Fig. 7b. Our calculations have allowed evaluation of possibilities of the two-energy method for substance determination in digital radiographic systems.

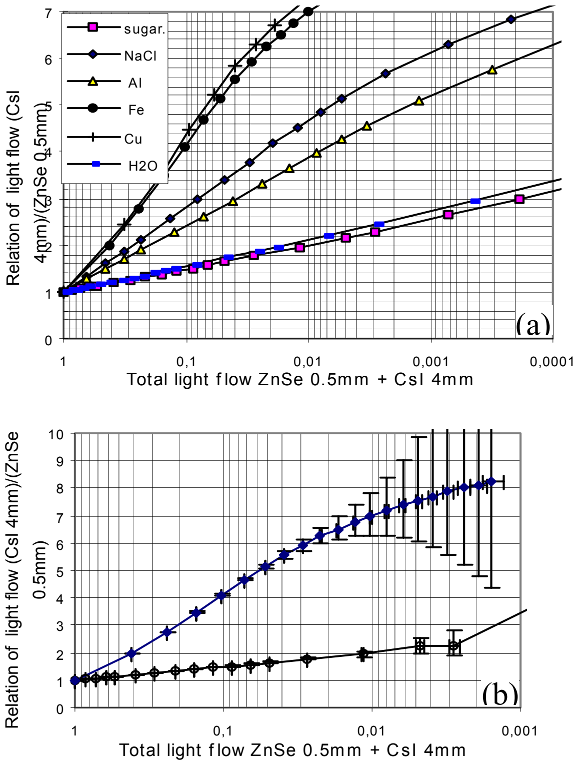


Fig. 7. The Determination of the composition of substance by 2-energy method. Two scintillators - ZnSe (0,5mm) and CsI (4mm).

It can be use d in inspection systems, including anti-terrorist activities, in technical diagnostics, medicine. An important point is combination of principles of multi-energeticity (reconstruction of substantional structure) and tomography (reconstruction of spatial structure). This allows creation of “multi-energy tomographs” – new instruments with unique possibilities in detection and diagnostics. This opens new prospects of broad application of the multi-energy approach in different fieldsof science andtechnology. It is essential that for reliable (close to 100%) detection of explosives and other forbidden substances and objects, chemical composition of the inspected objects should be reconstructed.

As most explosives are of organic origin, it is necessary to reconstruct the chemical formulas of organic compounds. They are composed, as a rule, of 3 or 4 main elements. Therefore, detection of explosives requires 3- or even 4-energy radiography. We have obtained theoretical expressions for relative (molar) concentrations of simple chemical components of a complex compound or a mixture of substances. This means a possibility of reconstruction of the chemical formulas of inspected substances and objects.

For identification of organic compounds containing two, three or all four main elements (hydrogen, carbon, nitrogen and oxygen) it is sufficient to use 2-, 3- or 4-radiography. As a whole, it allows distinction of organic materials both from inorganics and from other organics, and, consequently, to detect explosives on the background of inorganics or organics. The expected accuracy of such monitoring is 80-95%.

When we used scintillator with different atomic number, density and thickness, we can control objects with size from several mm to several m, Fig. 8.

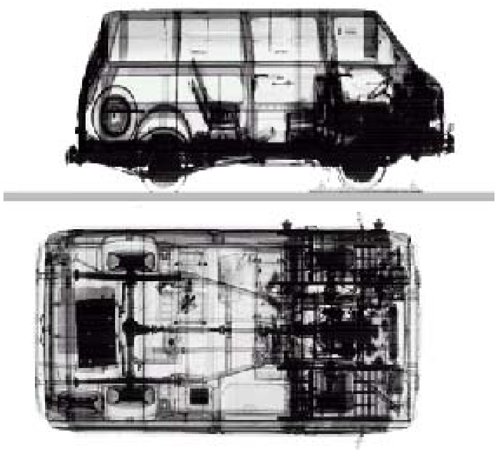


Fig. 8. Image car in x-ray.

If we used tomography principle, we can realize 3D imagination of different object and turn this one by special software and can see this one from different direction and so is inside. At our mind this method, coincide with multienergy possibility very promise for future inspection system.

Conclusions: In this paper there were tested wide class of objects with dimension from mm to several meters with absorption by steel equal from several μm to 250 mm.

For different objects and differen goal of control may be recomnend different type arrays and method of control.

Best spatial resolution is distinguished by used method of geometric optics or photoriceiver calls with integrats electronic and dispersed scintillator.

Best disclosure of dangerous materials, expecially explosive distiguish by used multienergy method, especially with scintillator with low density and atomic number – ZnSe(Te).

Control large objects was realized with used in detectors scintillator type CWO or CsI(Tl).Finally wide branch inspection instruments based on digital radiography method was installation and first 3D imegination was realized.

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