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Quantitative assessment of the quality of radiographic control, taking into account the specifics of generation and formation of working beams of penetrating radiation

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The paper presents a quantitative assessment of the quality of radiographic testing taking into account the features of formation of working beams of penetrating radiation by various design versions of deep collimation systems in portable radiographic testing devices of the shutter type equipped with sources based on the radionuclide ¹⁹²Ir, generating flows of ionizing radiation by focal spots of the emitting working surfaces "bottom" and "side" of the cylindrical capsule of the emitter. Mathematical modeling of the interaction of gamma radiation with elements of deep collimation systems of various geometries was carried out using the MCNP5 and Geant4 software packages. It was found that the use of a pyramidal deep collimation system allows improving the signal-to-noise ratio by approximately two times compared to a rectangular-pyramidal one, which helps to improve the quality of the recorded image and reduce the weight and size characteristics of the equipment. In addition, the orientation of the emitter capsule relative to the "zone of interest" by the focal spot of the emitting region "bottom" slightly increases the contribution of the noise effect and <1 % worsens the parameters of the "signal/noise" factor.

Keywords: deep collimated system; noise effect; signal-to-noise factor; gate-type gamma-ray flaw detector.

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The high quality of the radiographic inspection method, with a relative sensitivity of 1–2 % within a radiation thickness range of up to 70 mm as measured based on the steel, is reliably achieved by using commercial deeply collimated radiographic inspection equipment (RIE) of portable class. This equipment is typically fitted with standard radiation sources based on the radionuclide ¹⁹²Ir [1].

According to expert estimates, up to 10.000 commercial gamma-ray flaw detectors are in industrial operation in the Russian Federation at shipbuilding facilities, chemical, oil & gas, and petrochemical plants, as well as in the power generation sector.

The portable shutter-type gamma-ray flaw detector of "Stapel" series [2] developed by JSC

"NIITFA" to adapt to confined installation and repair conditions and equipped with a deep collimation system has become widely used.

The experience of using this RIE at shipbuilding enterprises has resulted in a hypothetical that the best sensitivity of the inspection method under conditions of deep collimation of the frontal radiation beam is achieved with standard radiation sources oriented towards an object under inspection solely with the emitting area of the bottom working surface of the cylindrical source capsule.

This hypothesis was preliminarily studied and evaluated using hole-type image quality indicator No. 2 (according to GOST 7512-82) at a shipbuilding enterprise under standard conditions for recording the macrostructure of welded joints.

The actual results from the reference quality assessment of radiographic inspection on real objects did not allow for favoring either coordinate system for focal spots of emitting areas (capsule "side" or "bottom"), with the source capsule oriented with its bottom or side surface relative to the "region of interest".

In this regard, the practical experience of radiographic inspection using the mentioned RIE and analysis of the structural design of the collimated radiation beam shaper in shutter-type gamma-ray flaw detectors suggests that a different approach is needed to study this issue by accounting for the specifics of shaping deeply collimated working radiation beams, for example, through quantitative assessment of radiation conversion effects and generation of scattered radiation noise flux (I_{ϕ}), which negatively affects the method's sensitivity, and the unscattered radiation flux (I_n) carrying the useful information, in a digital format.

In this context, considering the different physical capabilities for transforming the primary radiation flux by deep collimation systems of various structural designs, a quantitative assessment of the achievable inspection quality is advised by using digital technologies based on the "signal-to-noise" factor (I_n/I_{ϕ}), which will allow for evaluating the degree of image blurring caused by imperfections in the collimator's design solutions, the use of filters, as well as of radiation sources with non-standard activated core dimensions, including the geometric orientation of the source capsule within the system.

Thus, this paper is focused on establishing the "signal-to-noise" factor in relation to different deep collimation systems (pyramidal-rectangular, Fig. 1 (A1-A1) and pyramidal, Fig. 1 (A2-A2)) under the above described conditions of exposure with focal spots of "side" and "bottom" emitting areas of the cylindrical source capsule.

The radiographic inspection system for this case is presented in detail in Figure 1.

The interaction of photons from the ^{192}Ir radionuclide source [4] with the system components and the quantitative determination of I_{ϕ} and I_n fluxes registered by the film-emulsion detector [5] were implemented using the Monte Carlo mathematical modeling method with the MCNP5 software package according to the calculation model accounting for the coordination of focal spots in the "bottom" and "side" positions

within the system as applied to the cases of using the Pb filter and radiation sources, including those with non-standard activated core dimensions. The materials specified in the calculation model are: protection unit based on uranium-238, source holder made of VNZh-95 alloy, source capsule and socket bushing of the protection unit made of stainless steel 12Kh18N10T, and the active part based on ^{192}Ir .

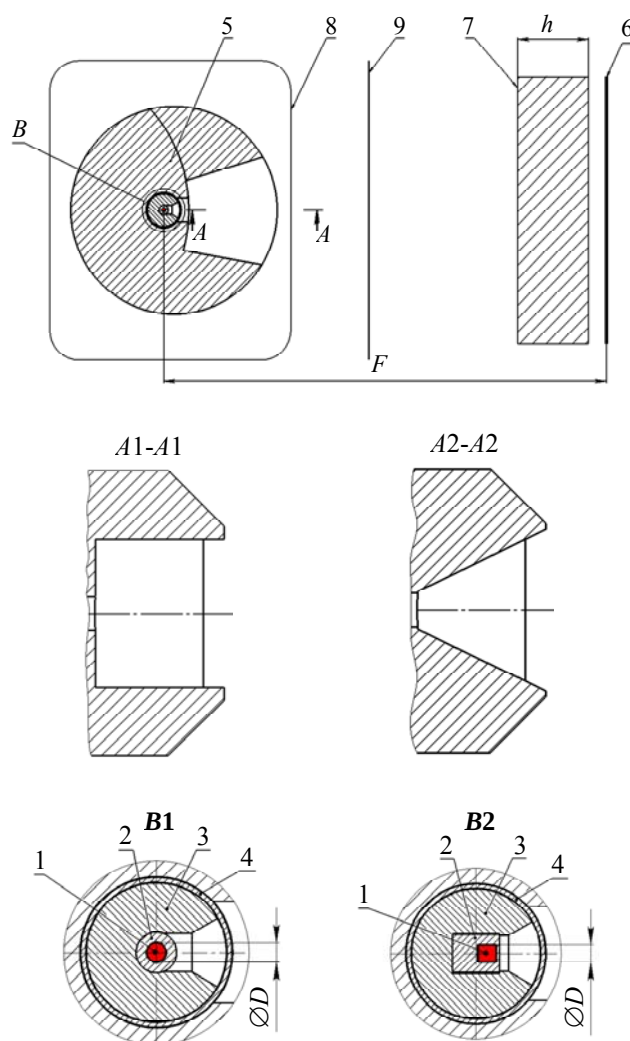


Fig. 1. Simplified radiographic inspection system: A1-A1 – cross-sectional view of the pyramidal-rectangular deep collimation system; A2-A2 – cross-sectional view of the pyramidal deep collimation system; B1 – focal spot of the "side" emitting area; B2 – focal spot of the "bottom" emitting area; 1 – active part of the radiation source; 2 – source capsule; 3 – source holder; 4 – sleeve; 5 – protective-collimation unit with a shutter; 6 – film detector; 7 – object under inspection; 8 – housing of the manual radiation beam coordination system; 9 – Pb filter

The modeling results accounting for the "signal-to-noise" using MCNP5 software package are presented in the table.

Visualized representations of the registered gamma-ray flux distributions for various structural designs of deep collimation systems were implemented by using Geant4 software package [6]. The modeling involved initiating 3.7×10^8 decay events applied to the radiation source based on the radionuclide ^{192}Ir , with an active part sized $\varnothing 1.5 \times 1.5$ mm and a focal length of 150 mm, followed by plotting flux distributions (Fig. 2) in the MATLAB environment and curves of flux intensity distribution along X and Y axes, without considering the contribution of scattered radiation (Fig. 3).

Figure 2 shows track maps of gamma-quantum distributions at the focal length of 150 mm, depending on the deep collimation system geometry.

The maximum size of the region of interest is 150×150 mm at the focal length of 150 mm, according to the Operation Manual for equipment of the "Stapel5 Se75 Ir192" type incorporating the deep collimation system.

The experiments in this paper used the portable shutter-type gamma-ray flaw detector "Stapel" equipped with the deep collimation system [2].

Table

Source of ionizing radiation Ir192 TU95.930-82	Signal-to-Noise Factor			
	Orientation of the emitting working surface: "side". Rectangular-pyramidal collimator	Orientation of the emitting working surface: "bottom". Rectangular-pyramidal collimator	Orientation of the emitting working surface: "side". Pyramidal collimator	Orientation of the emitting working surface: "bottom". Pyramidal collimator
Active part size of the source of ionizing radiation $\varnothing 1.5 \times 1.5$ mm	22.411 ± 0.0041	22.199 ± 0.0044	47.539 ± 0.0054	47.216 ± 0.0053
Active part size of the source of ionizing radiation $\varnothing 1.5 \times 1.5$ mm with 0.1 mm filter	21.619 ± 0.0054	21.411 ± 0.0053	46.964 ± 0.0073	46.463 ± 0.0073
Active part size of the source of ionizing radiation $\varnothing 1.5 \times 1.7$ mm	21.622 ± 0.0041	21.404 ± 0.0044	46.959 ± 0.0053	46.461 ± 0.0053
Active part size of the source of ionizing radiation $\varnothing 1.5 \times 1.7$ mm with 0.1 mm filter	21.431 ± 0.0053	21.167 ± 0.0053	46.714 ± 0.0074	45.963 ± 0.0073

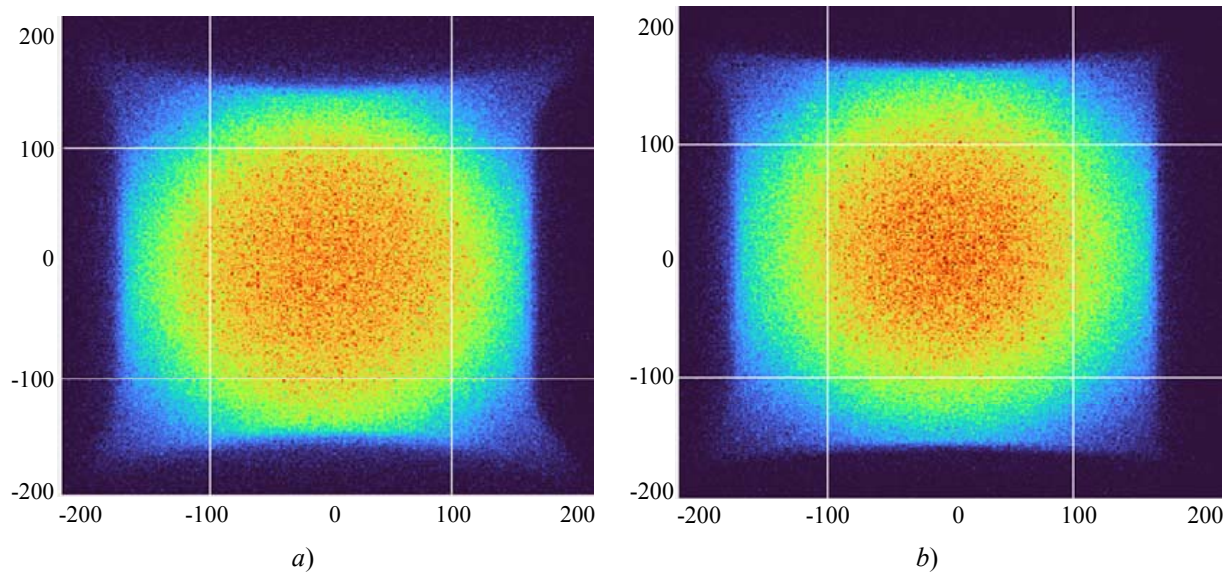


Fig. 2. Distributions of direct and scattered gamma-ray photon fluxes by deep collimation systems: a) – pyramidal-rectangular; b) – pyramidal.

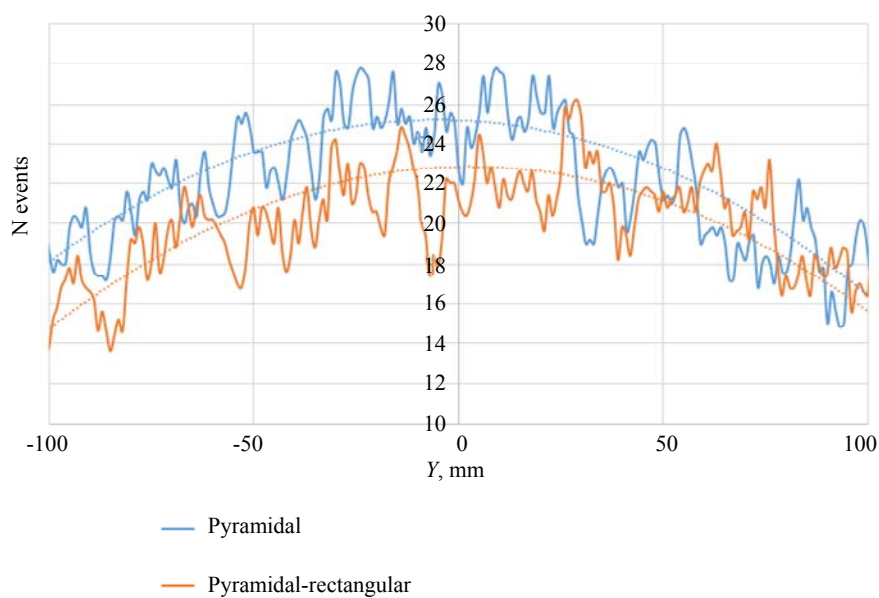
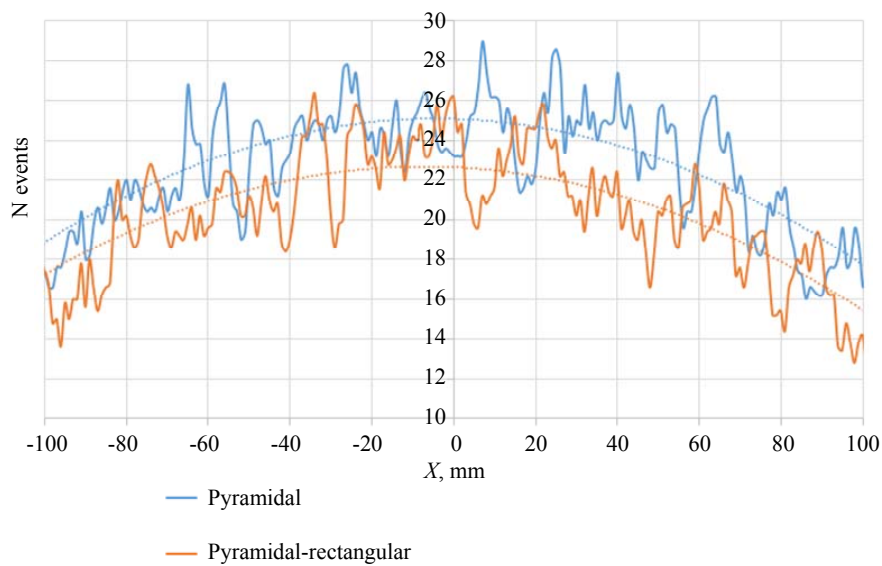


Fig. 3. Curves of flux intensity distribution along axes

The maximum size of the region of interest is 150×150 mm at the focal length of 150 mm, according to the Operation Manual for equipment of the “Stapel5 Se75 Ir192” type incorporating the deep collimation system.

The experiments in this paper used the portable shutter-type gamma-ray flaw detector “Stapel” equipped with the deep collimation system [2].

During testing of the specified commercial RIE in the confined conditions of the inspection zone, a key operational shortcoming was identified, which is the low precision in coordinating the conditional geometric axis of the collimated radiation beam with the center of the “region of interest” on the object under inspection. This negatively impacts the quality of recorded information due to the high probability of the irradiation zone shifting outside the “region of interest”, registering effects of backscattered radiation from adjacent structures, and increasing radiological hazards associated with higher radiation exposure to personnel and environment.

For this reason, JSC “EMI” has developed a patented technical solution (Patent No. 2791427) [7] for the updated model of the shutter-type gamma-ray flaw detector, which provides visualized coordination of the aiming trajectory for the center of the working gamma-ray beam in manual mode relative to the center of the “region of interest” on the object under study, which is marked with a point. This technical solution is implemented by modifying the standard foldable carrying handle equipped with a sharp-focus laser generator for the operator to perform visualized guidance of the virtual geometric axis of the directional path the gamma-ray beam by aligning the point projection of the narrow-directional

laser beam with the marked center of the “region of interest” on the object under study.

Conclusions

1. The calculated data for the “signal-to-noise” factor obtained using software packages indicate: the pyramidal deep collimation system improves the “signal-to-noise” ratio by ≈ 2 times (see the table) compared to the rectangular-pyramidal system, which should result in reduced image blurring.

2. According to the calculated data (table), the 0.1-mm thick Pb filter does not reduce the contribution of the noise effect.

3. Orienting the source capsule relative to the “region of interest” with the focal spot of the “bottom” emitting area slightly increases the noise contribution and degrades the “signal-to-noise” factor parameters by $< 1\%$ due to internal self-absorption. Therefore, orientation with the focal spot of the “side” or “bottom” emitting area is inconsequential.

4. The pyramidal deep collimation system allows reducing the weight of the shutter assembly by ≈ 1.4 times, thereby increasing its resistance to dynamic loads during emergency transportation.

5. The intensity of the direct unscattered radiation flux of the pyramidal deep collimation system is higher along X axis by 1.11 times and along Y axis by 1.1 times, as can be seen from the curves in Fig. 3.

6. Original technical solution No. 2791427 has been developed to enable the coordination of the virtual geometric axis of the collimated radiation beam relative to the “region of interest” in order to increase the precision and reduce noise effects from backscattered radiation.

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