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ON-LINE LUMINESCENT DOSIMETRY OF PRODUCT PROCESSING MODE AT AN ELECTRON LINAC

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Radiation-technological processes on the basis of electron accelerators, in particular, sterilization of medical devices, are regulated by international standards. The distribution of the electron flux density and absorbed dose are the main parameters of such processes, that require constant monitoring. In this work, we investigated the possibility to determine in real time the absorbed dose profile on the surface of an object processed using the effect of cathodoluminescence, that occurs when the electron flux acts on technical materials (mainly amorphous dielectrics). The results of calibration of the cathodoluminescent radiators of different composition against the absorbed dose measured by a calorimetric method are presented. The study of the novel technique at an LU-10 electron Linac of NSC KIPT made it possible to identify the sources of uncertainty and evaluate their contribution to the dose measurement.

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INTRODUCTION

By now there are about one and a half thousand industrial electron accelerators worldwide involved in radiation-technological processes. They process the products with a total value of over one hundred billion dollars yearly. This activity, especially radiation sterilization of medical devices, is regulated by international standards [1]. The sterilization process includes the installation of boxes with the treated products in transport containers, transfer of them to the zone of irradiation by a scanning electron beam with specified parameters, and return transportation to the unloading area. At the same time, the standard establishes the requirement of continuous monitoring of five key process parameters, including the distribution of the electron flux density on the surface of the irradiated object and the absorbed dose.

Currently, the disposable chemical dosimeters are mainly used for routine dosimetry. They are placed in the product before it is installed on the conveyor and removed from the unloading area with the subsequent dose measurement. This procedure usually takes about half an hour. If the accelerator mode changes during this time, then the output product may not meet the quality criteria. Therefore, the development of methods for on-line diagnostics of the radiation process is very topical.

In works [2, 3], the phenomenon of luminescence excited by a pulsed electron beam (cathodoluminescence, CL) in the technical dielectrics was described. Those materials, in particular, are the cardboard, from which the shipping containers for most types of products are commonly made, as well as a number of polymers widely used in radiation technologies (polypropylene, polyethylene, polystyrene, fluoroplastics, etc.). The main characteristics of CL were investigated and the possibility of using this phenomenon for the on-line control of electron flux profile, as well as the absorbed dose and dose rate on the surface of an irradiated object was shown. In this work, we studied the characteristics of various materials as promising CL detectors of the absorbed dose, as well as a method of their calibration.

1. CONDITIONS FOR USE OF CL FOR DIAGNOSTICS OF PROCESSING MODE

Industrial electron accelerators are operating mainly in a pulsed mode with pulse duration of $10^{-6}\ldots10^{-5}$ s at a particle energy of up to 10 MeV. The action of accelerated electrons on an amorphous dielectric is accompanied by incoherent optical radiation. Its nature is associated with the localization of electrons, injected by ionizing radiation from the valence band into the conduction band, on deep traps in the forbidden band of the dielectric. If the duration of the beam pulse is shorter than the characteristic time, determined by the filling rate of deep traps and their concentration, the intensity of the instantaneous component of the optical radiation is proportional to the absorbed dose rate on the surface of the treated object [3]

$$\tau_p << \frac{N_{DT}}{n_{CB}}\tau_{CB}\,, \qquad (1)$$

where τ_p is the beam pulse duration, N_{DT} is the concentration of vacant deep traps, n_{CB} is the concentration of electrons in the conduction band, τ_{CB} is the lifetime of the quasi-free electrons in the conduction band before being captured by a deep trap.

In this case, the absorbed dose rate is directly proportional to the electron flux density.

$$\dot{D} = \dot{\Phi}_e \frac{dE_e}{dz}\,, \qquad (2)$$

where $\dot{\Phi}_e$ is the electron flux density, $\frac{dE_e}{dz}$ is the average ionization loss of electrons per mass unit of their range in the material.

If an object moves through the irradiation zone with velocity V_c, when registering its optical radiation with exposure time

$$\tau_{reg} > \frac{d_b}{V_c}\,, \qquad (3)$$

where d_b is the transverse size of the beam on the surface of the object, and if condition (1) is satisfied, the value of the integral of the radiant luminosity of the object over the exposure time (CL yield) is proportional to the absorbed dose on its surface.

Since the irradiated objects are usually made of different materials with different radiation-optical yield, a thin CL radiator (having thickness much less than the electron range), being made of a specially selected material with high radiation resistance, can be used as a CL detector to unify the conditions of the dose measurement. Such a radiator can be placed on a transport container with the products and, after appropriate calibration, to provide the on-line monitoring of the electron flux density and absorbed dose [3].

2. CALIBRATION OF CL DETECTOR ON ABSORBED DOSE

The calorimetric method of measuring the absorbed dose [4] was used to calibrate the luminescent detectors. The RISO Polystyrene Calorimeter dosimeters (RISO Lab, Denmark) were applicated as the reference dosimeters. The routine chemical dosimeters Red Perspex 4034 (Harwell Dosimeters, UK) and B3 film (GEX Corporation, USA) were calibrated against the RISO Calorimeter. The latter provides the determination of dose averaged over its sensitive volume by 138 mm in diameter and 18 mm thick. The dosimetry systems Red Perspex 4034 and B3 provide possibility to measure the dose at a given place of an irradiated object. Their placement in the RISO phantom and combined irradiation with the calorimeter enables to control the accuracy of the routine dosimeters. To measure the CL yield, a set of radiators (CLR) of following composition was used:

1. CLR-1 (3 layers of polypropylene film by total thickness of 96 μm on an aluminum substrate with dimensions 550×300×1 mm);
2. CLR-2 (3 layers of polypropylene film by total thickness of 96 μm on a cardboard 4 mm thick).

The first radiator had also 5 cm horizontal scale marks.

The calibration was carried out on a linear electron accelerator LU-10 of NSC KIPT. The samples of radiators, together with the dosimeters, were placed on the two transport containers (Fig. 1) and moved at a given velocity through the zone of irradiation with a scanning beam. For calibration, 5 series of measurements were carried out with different average beam current and conveyor speed (Table 1). That provided the required absorbed dose range. The average beam current was changed stepwise by dividing the pulse repetition rate.

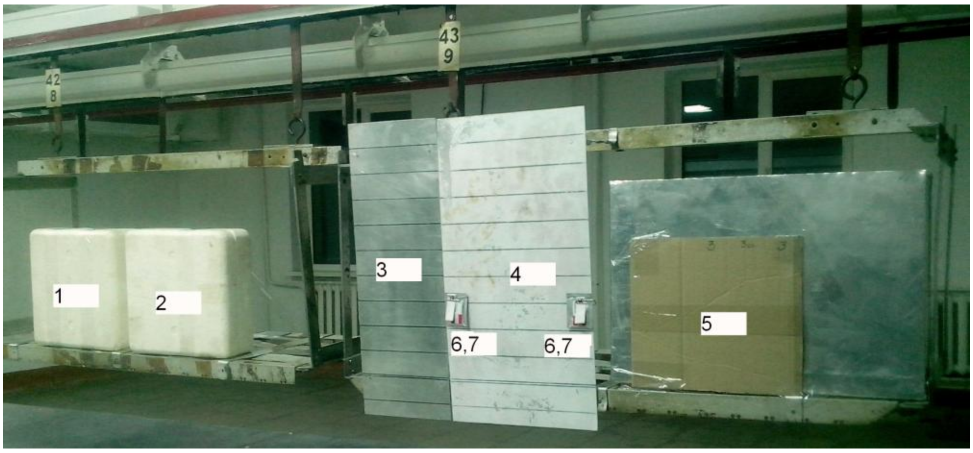

Fig. 1. Measuring devices used in calibration of CL radiators:
1 – RISO phantom with a B3 dosimetry film installed inside; 2 – RISO calorimeter; 3 – CLR-1; 4 – aluminum plate with dosimeters fixed on it; 5 – CLR-2; 6 – dosimetry film B3; 7 – dosimeter Harwell Perspex 4034

Table 1

Accelerator parameters during measurements

Measurement No.	Conveyor speed, cm/s	Average beam current, mA ±0.003	Most probable (average) energy of the beam, MeV	Scan width, cm
1	1.24	0.75	9.4 (11.3)	40.3
2	1.86	0.76	9.4 (11.3)	40.5
3	3.10	0.76	9.3 (11.2)	39.7
4	1.24	0.38	9.2 (11.1)	39.5
5	1.24	0.19	9.4 (11.3)	40.1

The measurement of CL radiation was carried out remotely using a controlled digital single-lens reflex camera (DSLR) Canon EOS XT with a specially designed mirror-lens optical channel mounted behind the radiation shielding of the accelerator. For the correct selection of the exposure, the light-signal characteristic of the DSLR matrix was preliminary investigated, and the range of its linear portion was established. The CL intensity in rel. units was determined by averaging the data over the vertical axis at a height of 130…150 mm from the lower edge of the transport container in the area of the Red Perspex and B3 dosimeter location. Fig. 2 shows a photo of the glow of the CLR-1 and CLR-2 radiators, taken during the calibration process, and Fig. 3 shows the dependence of the CL yield on absorbed dose, measured using the RISO calorimeter and B3 film.

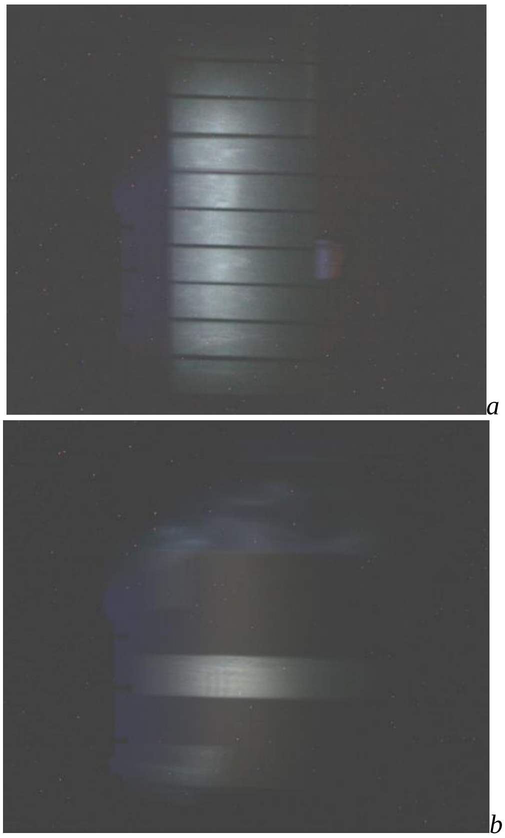

Fig. 2. Photo of CL-radiator glow:
CLR-1 (a); CLR-2 (b)

The results of the calibration are listed in Table 2. The dose values obtained by the B3 film, and also the CL intensity of the radiators were recalculated using the approximation parameters.

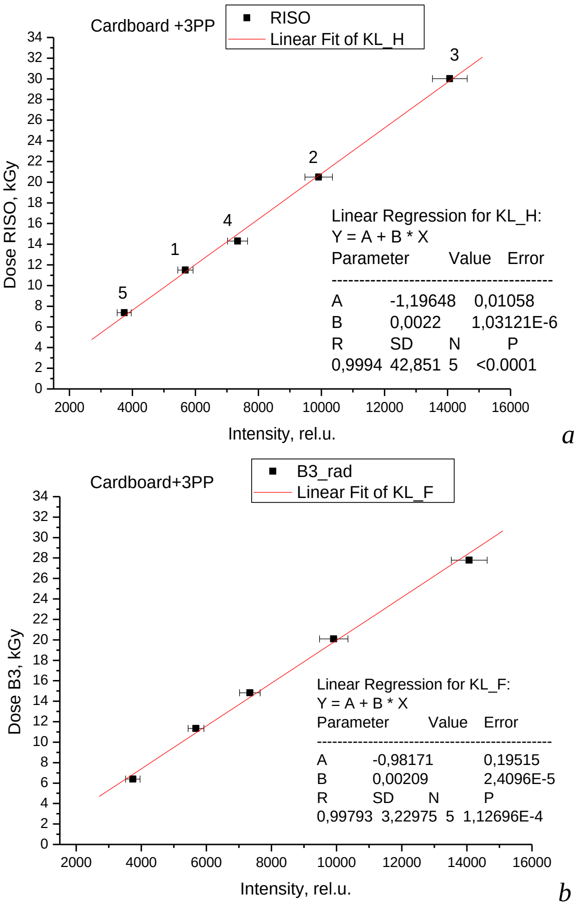

Fig. 3. Dependence of CL yield from CLR-2 radiator on the absorbed dos, measured by RISO calorimeter (a) and B3 film (b)

Table 2

Comparative results of absorbed dose measurement by different techniques

Measurement No.	Dose RISO, kGy	Dose Red Persp, kGy (Δ%)	Dose B3 in fantom, (calculated), kGy (Δ%)	Dose B3 on radiator, (calculated), kGy (Δ%)	Dose CLR-1, (calculated B3), kGy (Δ%)	Dose CLR-2, (calculated B3), kGy (Δ%)
1	11.5	12.0 (4.2)	12.3 (6.7)	11.3 (-1.4)	10.4 (-9.4)	10.9 (-4.1)
2	20.5	21.6 (5.2)	20.8 (1.7)	20.1 (-2.1)	18.6 (-7.9)	19.7 (-1.8)
3	30.0	33.7 (11)	29.5 (-1.7)	27.8 (-8.1)	29.2 (5)	28.4 (2.3)
4	14.3	14.4 (1.2)	14.8 (3.8)	14.8 (3.5)	15.4 (3.6)	14.4 (-3.3)
5	7.4	7.4 (0.2)	6.5 (-13.9)	6.4 (-15.3)	7.3 (12)	6.8 (6.4)

3. SOURSES OF UNCERTAINTY OF ABSORBED DOSE MEASURING BY CL TECHNIQUE

The possible sources of uncertainty when measuring the dose by the intensity of the CL signal can be conventionally subdivided into 4 groups:

- distortions associated with the material of the radiator;
- variations in the position of the CL radiator's plane relative to the optical axis of the measuring channel;
- distortion of the optical path;
- distortion of photoelectric conversion.

The distortions associated with the CL radiator's material can be caused by its inhomogeneity, and also by the degradation resulting in the change of detector's radiation-optical output over time. This can be controlled by periodic calibration using the validated dosimetry methods. If the CL radiator is prepared by coating, then the special attention should be paid to the uniformity of its thickness. The analysis of the data obtained during the calibration procedure showed, that the standard deviation of the CL intensity for radiators made of cardboard and polypropylene does not exceed 5%.

The variations of the CL intensity when changing the angle of its registration relative to the radiator plane from 0 to 10° horizontally and vertically does not exceed 2%.

The distortions in the optical path are possible due to inaccurate alignment of its elements. A specially designed stand was used to mount the elements of the mirror-lens optical path. The geometric distortion of the lens can be neglected, because its focal length (200 mm) is much higher than the linear dimensions of the APS-C DSLR matrix (22.2×14.8 mm).

The distortion in the photoelectric converter is possible if the photographic exposure is incorrectly set, i.e. when going beyond the linear portion of the light-signal characteristic of the camera matrix.

The distortions in the data transmission channel can be eliminated because information is transmitted digitally.

CONCLUSIONS

The CL dosimetry method can be considered as an extension of the well-known luminescent methods of the solid state dosimetry (the thermoluminescent, photoluminescent dosimetry, etc. Fig. 4). However, those methods are mainly passive, because they are based on registration of optical radiation from pre-irradiated detectors made of special materials, stimulated by various kinds of external influences. The proposed method is active, because provides the dosimetry information directly during the radiation exposure and without additional stimulation.

In contrast to the scintillation method, which is also active, the cathodoluminescent technique extends to the high-dose region. That enables to use it in radiation-technological processes. For the scintillation method, the detectors with the high concentration of the emission centers (~ 10^{21} cm^{-3}) are used. This makes it possible to provide measurements in the range of small doses. Conversely, the CL method provides the possibility to register an optical signal in the industrial range of absorbed doses using routine technical materials (polypropylene, cellulose, etc.) with low concentration of emission centers (~ 10^{18} cm^{-3}).

In the radiation technologies, a number of dosimetry systems are applied [5]. Thus, Fig. 4 shows the classification of known methods of solid-state dosimetry in a wide range of doses, used both for biological and industrial purposes, with the indication of physical effects underlying them, as well as the place of the cathodoluminescent technique.

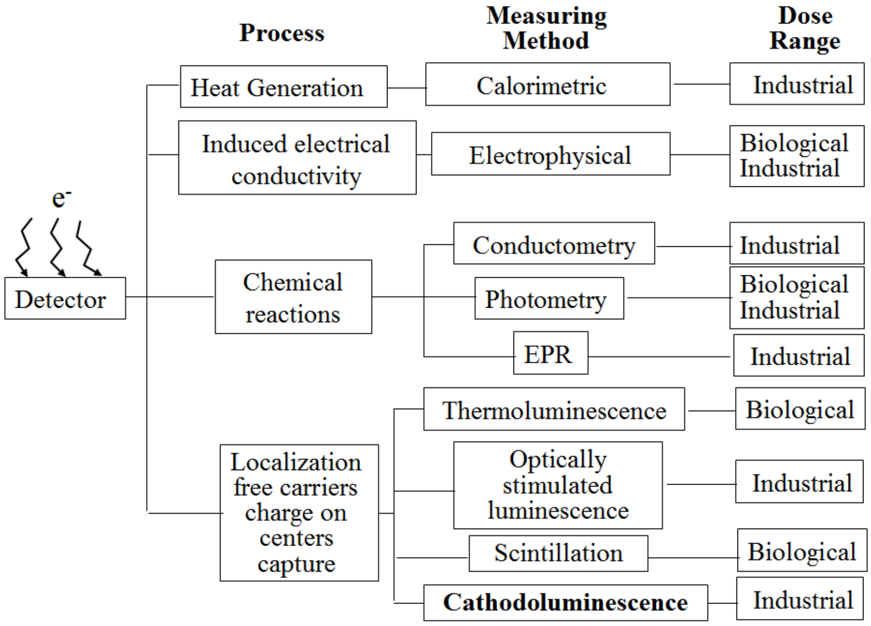

Fig. 4. Solid state dosimetry methods

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ЛЮМИНЕСЦЕНТНАЯ ON-LINE ДОЗИМЕТРИЯ ОБРАБОТКИ ПРОДУКЦИИ НА УСКОРИТЕЛЕ ЭЛЕКТРОНОВ

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Радиационно-технологические процессы с применением промышленных ускорителей электронов, в частности стерилизация изделий медицинского назначения, регламентируются международными стандартами. Основными параметрами таких процессов, требующими постоянного контроля, являются: распределение плотности потока электронов и поглощенная доза излучения. Исследована возможность применения эффекта катодолюминесценции, возникающей при воздействии потока электронов на технические материалы (главным образом, аморфные диэлектрики) для определения в режиме реального времени профиля поглощенной дозы на поверхности обрабатываемого объекта. Приведены результаты калибровки катодолюминесцентных радиаторов разного состава по поглощенной дозе с применением калориметрического метода. Апробация нового метода на ускорителе электронов ЛУ-10 ННЦ ХФТИ позволила установить источники неопределенности и оценить их вклад в результат измерений.

ЛЮМІНЕСЦЕНТНА ON-LINE ДОЗИМЕТРІЯ ОБРОБКИ ПРОДУКЦІЇ НА ПРИСКОРЮВАЧІ ЕЛЕКТРОНІВ

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Радіаційно-технологічні процеси із застосуванням прискорювачів електронів, зокрема стерилізація виробів медичного призначення, регламентуються міжнародними стандартами. Основними параметрами таких процесів, що вимагають постійного контролю, є розподіл щільності потоку електронів і поглинута доза випромінювання. Досліджена можливість застосування ефекту катодолюмінесценції, яка виникає при дії потоку електронів на технічні матеріали (головним чином, аморфні діелектрики) для визначення в режимі реального часу профілю поглинутої дози на поверхні оброблюваного об'єкта. Наведено результати калібрування катодолюмінесцентних радіаторів різного складу за поглинутою дозою із застосуванням калориметричного методу. Апробація нового методу на прискорювачі електронів ЛП-10 ННЦ ХФТІ дозволила встановити джерела невизначеності та оцінити їх внесок у результат вимірювань.