About the features of the design of X-ray systems for nondestructive control in industry

V B Bessonov, A V Obodovskiy and Y N Potrakhov
Saint-Petersburg Electrotechnical University “LETI”, 197376, Saint-Petersburg, Russia
E-mail: vbbessonov@yandex.ru

Abstract. X-ray methods for nondestructive control take the priority place if necessary to exercise quality control of a product, to define presence of defects and to execute expert researches. In the present work, an attempt is made to systematize some features in the design and construction of installations for X-ray non-destructive control using the example of developments conducted at St. Petersburg State Electrotechnical University “LETI”.

X-ray methods for nondestructive control take the priority place if necessary to exercise quality control of a product, to define presence of defects and to execute expert researches. At the same time, a significant proportion of research is carried out in stationary conditions on the basis of specialized laboratories. Obviously, for such applications it is necessary to create appropriate conditions for work, primarily on the basis of modern safety requirements when working with ionizing radiation sources, taking into account also the nomenclature of objects that need to be studied and the requirements for research quality. The quality of the research in this case refers to the achievement of specified image characteristics, allowing to judge about the presence or absence of defects. These features primarily include:

– spatial resolution;
– contrast;
– the ratio of signal to noise;
– dynamic range [1].

In the present work, an attempt is made to systematize some features in the design and construction of installations for X-ray non-destructive control using the example of developments conducted at St. Petersburg State Electrotechnical University “LETI”.

Over the past few years there have been significant changes in the sanitary rules on the territory of the Russian Federation. Significantly revised documents were issued:

– sanitary rules and regulations sanitary rules and norms 2.6.1.3289-15 “Hygienic requirements for ensuring radiation safety when dealing with sources generating X-rays at an accelerating voltage of up to 150 kV”;
– sanitary rules and regulations sanitary rules and norms 2.6.1.3164-14 “Hygienic requirements on ensuring radiation safety at X-ray defectoscopy”.

It is known that work with sources of ionizing radiation requires the license for the related activity which obtaining is accompanied by a number of events. However, in accordance with paragraph 1.7.2 “Basic sanitary rules of ensuring radiation safety”. Exempt from control after registration of a sanitary
and epidemiological certificate: electrophysical devices generating ionizing radiation, in all possible modes and conditions of operation, which is the ambient dose equivalent dose rate in any available point at a distance of 0.1 m from the outer surface of the device does not exceed 1.0 µSv/h. Under any possible operating modes product means any modes that a user can install without breaking the design or the seal manufacturer.

It should be noted that the only document currently confirming the radiation safety of the device generating ionizing radiation is the expert opinion of an accredited laboratory. In this case, the conclusion on the possibility of operating the installation without license can only be issued by the head scientific institution of Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing.

If this condition is met, obtaining permission to operate ionizing radiation sources is greatly simplified and looks as follows:

1. Submissions to Territorial Department of Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing on the territorial subject of the Russian Federation of allowing documentation (expert opinion, certificate of conformity);
2. Agreements of the application for supply with the territorial department of Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing for the subject of the Russian Federation (this item is not required in accordance with p. 3.5.1 “Basic sanitary rules of ensuring radiation safety” (however, it is recommended to perform it);
3. Training of a specialist responsible for radiation safety at the enterprise;
4. Notice Rospotrebnadzor of the implementation on the delivery the source of ionizing radiation;
5. Application and receipt of a sanitary and epidemiological certificate.

As already noted, one of the most significant requirements is the need to ensure radiation safety.

At the moment, in practice, there are three main methods for calculating protection from ionizing radiation (X-ray):

– experimental (in practice it is rarely used);
– on the basis of universal tables for calculations of protection from photon radiation of point isotropic sources;
– based on nomograms and characteristics of the X-ray tube.

The use of universal tables for the calculation of protection against photon radiation allows us to easily estimate the thickness of the necessary protective layer. Nevertheless, in view of a number of assumptions, such a calculation cannot be called accurate enough:

– the data in the tables are given for monoenergetic radiation sources;
– there is no account for secondary (scattered) radiation;
– there is no account for the characteristic radiation [2].

Despite these assumptions, apply a specified method of bringing continuous Bremsstrahlung process spectrum from X-ray tube to monoenergetic using the formula:

$$E = \frac{2}{3} eU,$$

where $E$ – effective energy of quanta in the spectrum, keV; $e$ – charge of electron; $U$ – accelerating voltage, kV. Thus, for an accelerating voltage of 150 kV, the effective energy of quanta in the spectrum is 100 keV.

Knowing the radiation pattern (capacity ambient dose equivalent in different directions), it is possible, using reference tables from [2], to determine the required value of the cover thickness.

More accurate is the calculation of protection based on the calculation of nomogram parameters. Parameter of nomograms is the coefficient

$$k_i = 2.5 \times \frac{D_r}{D_{r_i}} \times m \times \frac{i}{R^2} \times N,$$
where $\dot{D}_r$ – radiation output of a specific X-ray tube for which protection is determined; $\dot{D}_0$ – radiation output of some standard X-ray tube; $m$ – the ratio of the maximum permissible design dose rate for the premises of permanent stay of personnel of category A at a 36-hour working week to design dose rate for the given conditions; $i$ – current in the x-ray tube, mA; $R$ – distance from the anode of the X-ray tube to the calculation point; $N$ – directivity factor (for a direct beam $N = 1$, for scattered radiation $N = 0.05$).

**Table 1.** Table for calculating protection against ionizing radiation with an average energy of $E = 100$ keV.

| Rate of attenuation | Concrete | Cover thickness, cm |
|---------------------|----------|---------------------|
|                     | Steel    | Plumbum             | Tungsten            |
| 1.5                 | 4.9      | 0.26                | 0.02                | 0.01                |
| 10                  | 12.1     | 1.1                 | 0.08                | 0.04                |
| $10^2$              | 19.6     | 2.1                 | 0.17                | 0.08                |
| $10^3$              | 26.6     | 3.0                 | 0.28                | 0.12                |
| $10^4$              | 33.4     | 4.0                 | 0.38                | 0.17                |
| $10^5$              | 40.2     | 4.6                 | 0.5                 | 0.22                |
| $10^6$              | 46.8     | 5.7                 | 0.61                | 0.27                |
| $10^7$              | 53.4     | 6.6                 | 0.72                | 0.32                |

**Figure 1.** Nomograms for calculation of protection from plumbum.

Protection is calculated based on the nominal current and voltage values of the X-ray tube. The table of power of an exposition dose of X-ray radiation (beam return) is usually provided in technical documentation on X-ray tubes and devices under the set measurement conditions (table 2).
Table 2. Data on the dose power of X-ray radiation from a X-ray tube for the device INTROVOLT 100BE

| Device type | Tube type   | Exposure dose rate, R/min | Measurement conditions |
|-------------|-------------|---------------------------|------------------------|
| INTROVOLT 100BE | 1BPV15-100 | 40                        | 500                    |
|              |             | 100                       | 10                     |

From the data presented in table 2 it is possible to determine a radiation exit of a X-ray tube by the following formula:

$$ D_T = \left( \frac{R}{\min} \right) \times R \left( \frac{m^2}{mA} \right) \times 10 $$

where, according to table 2, $\dot{X}$ – exposure dose rate; $R$ – distance; $i$ – beam current; 10 – transition coefficient from R to Gy. Substituting these values we get:

$$ D_T = \left( \frac{40 \times 0.25 \times 10}{10} \right) = 10 \left( \frac{mGy \times m^2}{mA \times min} \right). $$

Next, it is necessary to determine the maximum permissible dose rate for the premises of the relevant categories of personnel (population). The permissible dose rate is determined taking into account the dose limit per year with a safety factor of 2 according to formula:

$$ AD_0 \left[ \frac{\mu Sv}{hour} \right] = \frac{DL \left[ \frac{\mu Sv}{year} \right]}{2 \cdot 1700 \left[ \frac{hour}{year} \right]}. $$

The dose limit for Personnel A is 20 mSv/year, for Group B personnel – 5 mSv/year, for the population – 1 mSv/year. Then allowable dose ($AD_0$) for the personnel of group A is 6 mSv/h, for the personnel of group B – 1.5 mSv/h, for the population – 0.3 mSv/h.

The radiation output of a standard X-ray tube is determined graphically by reference [2].

It should be noted that in practice, a combined approach to the definition of protection is often implemented. Also effective is the collimation of the X-ray beam by lead diaphragms. With the help of this technique, it is possible to significantly reduce the mass-dimensional characteristics of the equipment by using a “two-stage” protection against ionizing radiation.

Thus, the main approaches to the organization of protection against ionizing radiation when designing installations for nondestructive control in the industry are considered.

Acknowledgments
The Russian Science Foundation have supported this work as the project entitled “The robotic system is multi-view X-ray microfocus aircraft parts and assemblies made of polymer composite materials with complex action”. Project number 16-19-00155.

References
[1] Potrakhov N N, Gryaznov A Yu, Potrakhov Ye N and Bessonov V B 2015 Vakuumnaya tehnikha i tekhnologiya 2 153
[2] Mashkovich P and Kudryavtseva A V 1995 Zashchita ot ioniziruyushchikh izluchenii (Moscow: Energoatomizdat)