Atlantis Highlights in Material Sciences and Technology (AHMST), volume 1
International Symposium "Engineering and Earth Sciences: Applied and Fundamental Research" (ISEES 2019)

Instrument Requirements for Accuracy of Ionizing Radiation Measurement in Environmental Monitoring

Orlik L.K.
Faculty of information technology
Russian State Social University
Moscow, Russia
Lubov.orlik@gmail.com

Zhukova G.S.
Department of Data Analysis, Decision-Making and Financial Technology
Financial University under the Government of the Russian Federation, Moscow, Russia
galsevzhukova@mail.ru

***Abstract* – The problem of radiation contamination makes the control relevant based on monitoring studies of large areas and large masses of the population. The issue of the development of measuring equipment base is relevant. The main quality indicator of radiation monitoring devices are random measurement errors. Quantitative assessment of technical efficiency of dosimetric monitoring devices is the expectation of the output effect. The relation between the probability of damage is not lower than the given degree of severity and magnitude of the acting damaging factor is called factorial law of damage. There are four types of law: conditional static, conditional dynamic, unconditional static, unconditional dynamic. The specific type of law is determined by experimental data. The probability density function of the random value of the radiation dose measured by the device is described by logarithmically normal law. In the field of small and large values of radiation doses, the conditional static and conditional dynamic laws practically do not differ. Therefore, measurement errors by the device of radiation doses are not so significant. In the area of radiation dose values, where the differences between two laws under consideration can reach rather large values, the maximum deviation of conditional dynamic law from the conditional static one is used. By setting the permissible value of the maximum discrepancy between two laws, it seems possible, in case of solving the inverse problem, to justify permissible errors in measuring radiation doses by a radiation device. Since the dose of radiation at a given point in time after an accident of a radiation-hazardous object can always be used to estimate the dose of radiation for a given exposure.**

Keywords* – *dosimetric monitoring; quality of radiation monitoring devices; factorial damage law; log-normal law; radiation dose.

I. INTRODUCTION

The technological revolution in the life of mankind, associated with the introduction of nuclear energy, has opened up unprecedented opportunities to solve many problems of social, economic and medical nature. There is no alternative to nuclear power, which provides large-scale energy production. A necessary condition for the informed choice of optimal technology options is consequences assessment of radioactive pollution of the environment. Radioecological issues include monitoring the biological effects of ionizing radiation, scientific substantiation of allowable limits of radiation doses and the development of methods to assess the dose loads on humans and biota. The problem of reducing radiation doses is global. Sources of radiation danger are not only the natural background radiation, nuclear accidents, the extremist use of RDD, but also the so-called peaceful atom. These are millions of tons of building materials containing natural radionuclides, sterilized dressings and medical products, interventional methods for diagnosing and treating malignant neoplasms, grain disinsection and presowing seed irradiation in agriculture.

Natural sources of ionizing radiation are major radiation hazard. Outside the polluted areas of the Earth, the dose of radiation per person is about 0.4–0.5 rem / year, including from natural sources - up to 0.3 rem / year. At the same time, the collective dose of natural exposure of the population, amounting to 5964 million man-bears over 70 years of life, is more than 200 times higher than the radiation load from the accident at the Chernobyl nuclear power plant [7,8]. At present, nuclear energy has been formed into a large branch of energy production. At 450 nuclear power units with a total capacity of at least 350000 MW (e), more than 16% of the total electricity in the world is generated. In Russia, it is 13.06% of electricity generation at all domestic power plants. Thus, one of the most urgent and socially significant tasks is to ensure the radiation monitoring of personnel, the public and the environment in the region of operating and decommissioned nuclear power plants [1-6].

At the beginning of the new millennium, the threat of access to the network's weapons of mass destruction — global terrorism — came to the fore. The act of nuclear terrorism can be carried out with the help of the so-called “dirty bomb” - a device for radiological dispersal, exploded by ordinary dynamite. Obtaining a radiological dispersal device RDD is one of the targets of terrorists. Another more ambitious danger is associated with nuclear power plants. At gunpoint terrorists are nuclear power plants [9, 10].

To ensure work safety at the facilities of nuclear industry, nuclear energy and space stations of a new generation, when disposing of nuclear waste and monitoring in radioactively contaminated areas it is necessary to develop electronics to operate in extreme conditions, namely, elevated levels of radiation, chemical activity and ultra-high temperatures. The research carried out on future-generation accelerators at CERN and the modernization of the Large Hadron Collider (LHC) require instruments to provide long-term dosimetric monitoring in the internal tracks of nuclear facilities.

Copyright © 2019, the Authors. Published by Atlantis Press.
This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

The problem of radiation contamination makes the control relevant based on monitoring studies of large areas and large masses of the population. In this connection, the issue for the development of measuring equipment base is relevant in accordance with the concept of the nature of the radiation hazard.

II. Problem statement

Quality measures for functioning of radiation monitoring devices and feasibility of using them to perform specified functions is technical efficiency. A quantitative estimate of technical efficiency of dosimetric monitoring devices is the expected value of the output effect. The main impact on the technical efficiency of the devices have systematic and random errors in measuring the dose rate and radiation dose. Systematic errors can be reduced to zero using the instrument setup. Therefore, in the future we will only talk about random measurement errors - as the main indicator of the quality of radiation monitoring devices.

III. Research Questions

The subject of research is operation technical efficiency of radiation monitoring devices.

IV. Purpose of the Study

The purpose of the paper is methods to substantiate the requirements for radiation monitoring instruments for measuring accuracy.

V. Research Methods

In the future, we will only talk about radiation dose meters and their technical efficiency.

As an output effect, we will consider the probability of damage to a biological object, depending on the level of the damaging factor, namely, the radiation dose measured by the device.

Due to the individual characteristics of the organism, the attainment of a definite effect on the destruction of a biological objective requires its own magnitude of a damaging factor. That is why the magnitude of the damaging factor — the radiation dose causing a certain effect of the lesion is considered as a random variable. Since the radiation dose measured by the device is a random variable, the probability of damage to a biological object, which is determined taking into account the readings of the device, will also be random.

The relation between the probability of a lesion is not lower than the given severity and magnitude of the acting damaging factor is called the *factor lesion law* (FLL) [11].

In its most general form, this law has the form

$$P = \int_0^L f(L)dL \tag{1}$$

In accordance with the definition of technical efficiency, we will find the expectation of the output effect — a random probability of damage and no less than a given severity based on the results of measuring the radiation dose (radiation dose rate) by a means of radiation monitoring

$$M[P] = \int_0^\infty P(L)\cdot f(L)\cdot dL. \tag{2}$$

Let us identify the following types of factorial effects. Let L50 denote the median value of the radiation dose, that is, the dose, when exposed to which, with a probability of 0.5, the object will experience the specified response.

With a deterministic approach, taking into account the variability of the reaction of biological objects to the effects of the damaging factor at a fixed L, we have the *conditional static* FLL:

$$P\text{ус}= P(L;L_{50}) = \int_0^L f(L)dL$$

Taking into account not only the variability of the response of biological objects to the effects of the damaging factor at a fixed L50, but also the random nature of the current dose, we have the *conditional dynamic* FLL:

$$P_{\text{уд}}= M[P(\tilde{L};L_{50})] = \int_0^\infty P(L;L_{50})\, f(L)dL$$

If, in addition to the variability of the response of the bio-object, we also take into account the random nature of Le, then we obtain the *unconditional static* FLL:

$$\text{P}_{\text{БС}}= M[P(L;\tilde{L}_{50})] = \int_0^\infty P(L;L_{50})\, f(L_{50})dL_{50}$$

finally, taking into account the random nature and dose and estimating the parameter Le, the *unconditional dynamic* FLL is obtained:

$$\text{P}_{\text{БД}}=\text{M}[\, P(\tilde{L};\tilde{L}_{50})] = \int_0^\infty\int_0^\infty P(L;L_{50})\, f(L)\, f(L_{50})dLdL_{50}$$

FLL types are shown schematically in Fig.1, where 1 - conditional static, 2 - conditional dynamic, 3 - unconditional static, 4 - unconditional dynamic.

The specific type of lesion factor law is determined from experimental data [12].

VI. Results

The probability density function of the random dose of radiation measured by the device, $\varphi(L)$ can be described by a logarithmically normal law with parameters: median radiation dose L_e and the law setting (σ_{lnL}.– standard deviation lnL).

$$\varphi(L) = \frac{\sqrt{K_{\ln L}}}{\sqrt{\pi}\cdot L}\cdot e^{-K_{\ln L}\ln^2\frac{L}{L_e}}. \tag{3}$$

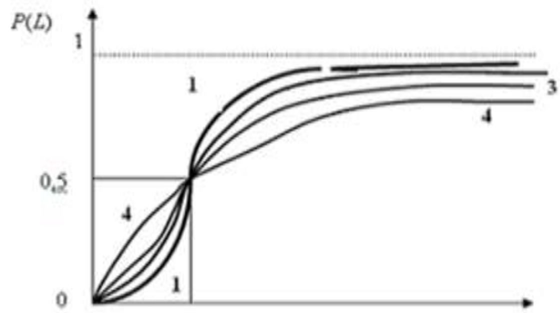

Fig. 1. Types of factor laws of defeat

We use the lognormal probability distribution law to describe the effect of ionizing radiation on a bio-object [13]. A random variable has a log-normal distribution if its values are multiplied by many independent factors, including latent ones, among which there is no dominant one. In the case of a lognormal distribution (3), the conditional static factorial lesion law is

$$P_{УС} = P(L; L_{50}) = \frac{1}{2}\left[1 + erf\left(\frac{1}{\sqrt{2}\sigma_{\ln L}} \ln \frac{L}{L_{50}}\right)\right] \quad (4)$$

Substituting the equation (3) and (4) into the formula (2) and completing the integration, we obtain the so-called conditional dynamic FLL

$$M[P] = 0{,}5\left[1 + erf\left(\sqrt{K_Д} \ln \frac{L_e}{L_{50}}\right)\right], \quad (5)$$

where $L_e = M(L)e^{-\frac{1}{4K_Д}}$ – median random value of radiation dose determined by instrument readings, $K_Д = \frac{KK_{\ln L}}{K + K_{\ln L}}$ – conditional dynamic parameter FLL .

The relation of conditional static and conditional dynamic laws is shown in Fig.2 by the number 1 in the graph is conditional static FLL, and number 2 - conditional dynamic FLL.

The equation analysis shows (5), that when an error in measuring the radiation dose $\sigma_{\ln L} \to 0$ and, consequently, $\sqrt{K_{\ln L}} \to \infty$, $\sqrt{K_Д} \to \sqrt{K}$, and $L_e \to M(L)$, and curves 1 and 2 on the graph, respectively, merge. As the measurement errors of radiation dose increase, the parameters of conditional dynamic FLL differ more and more from the similar parameters of the conditional static FLL, and curves 1 and 2 increasingly diverge.

The analysis of the curves in Fig. 2 shows that with increasing radiation dose, the differences between the two FLLs first increase, and then decrease, and for some value of the radiation dose, both laws coincide. With a further increase in radiation doses, the differences again begin to increase to a certain maximum value, and then again they tend to zero. Thus, at a qualitative level, it can be concluded that in the region of small and large radiation dose values, the conditional static and conditional dynamic RHFs do not practically differ. Therefore, measurement errors by the instrument for radiation doses by the device are not so significant from the point of view of biota state assessment. In a certain range of radiation dose values, the differences between the two considered FLLs can reach rather large values.

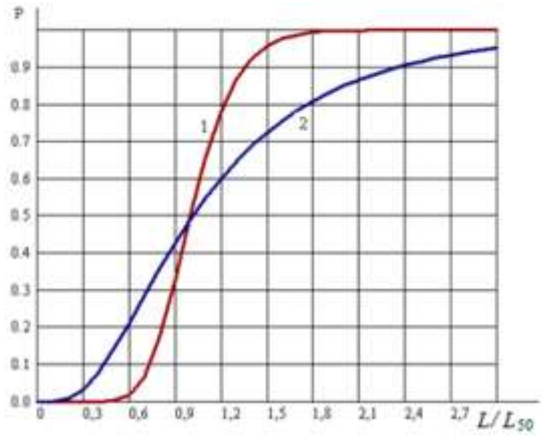

Fig. 2. Conditional static FLL (1) and conditional dynamic FLL (2).

To quantify the degree of divergence of two curves, we construct the function $\Delta P = M(P) - P = f(L)$, its graph is given in Fig.3.

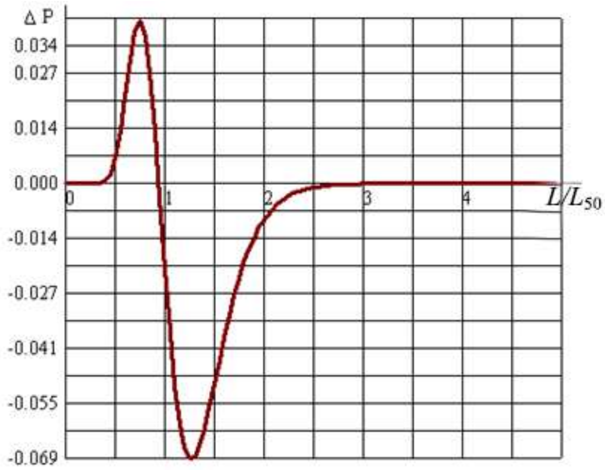

Fig. 3. The nature of the change in the value ΔP depending on the size of the radiation dose measured by the device

The graph of the function has two extremums that can be found by taking the derivative $\frac{d(\Delta P)}{dL}$ and equating it to zero.

Performing a series of transformations, we obtain a quadratic equation for the natural logarithm of the sample mean radiation dose

$$\frac{K^2}{K+K_{\ln L}}\cdot\ln^2\overline{L}-\frac{K}{2\left(K+K_{\ln L}\right)}\cdot\ln\overline{L}-$$
$$\frac{K}{16K_{\ln L}\left(K+K_{\ln L}\right)}+\ln\sqrt{\frac{K_{\ln L}}{K+K_{\ln L}}}=0$$

Roots of quadratic equation

$$\overline{L}_{1,2}=e^{\frac{1}{4K}\left\{-1\pm\sqrt{\frac{K+K_{\ln L}}{K_{\ln L}}}\cdot\sqrt{1+8K_{\ln L}\cdot\ln\frac{K+K_{\ln L}}{K_{\ln L}}}\right\}} \tag{6}$$

are the extremum points of the function $\Delta P=f\left(L\right)$

The analysis of the equation (6) for the roots of the equation $\Delta P=f\left(L\right)$ show that the maximum of the function is observed if we take the minus sign in the expression for the roots in curly brackets, and the minimum if we take the plus sign. And the minimum is the global extremum of the function $\Delta P=f\left(L\right)$. Such function $\Delta P=f\left(L\right)$ may be definied by: $\Delta P=P-M\left(P\right)=f\left(L\right)$, the sign of global extremum does not play a fundamental role. Since all other things being equal, the numerical value of the maximum $\Delta P\left(L\right)$ depends on measurement errors of radiation dose by the device, then, given the permissible value of the maximum value ΔP seems possible, by solving the inverse problem, to justify the permissible errors in the measurement of radiation doses by a radiation reconnaissance devic.

VII. Conclusion

The maximum deviation of the conventional dynamic FLL from the conventional static, depending on the accuracy of measuring the radiation dose, varies in a certain range. By setting the value $\left|\Delta P_{max}\right|$, it is possible to obtain permissible measurement errors of radiation dose by the device. Since the dose of radiation at a given point in time after the accident of a radiation-hazardous object can always be used to estimate the dose of radiation for a given exposure

$$L=K_{доз}\dot{L}_t,$$

where $K_{доз}$ – dose coefficient.

The considered approaches make it possible at the theoretical level to substantiate the requirements for radiation reconnaissance devices according to the accuracy of measuring the dose rate and radiation dose.

To characterize the deviation of one law from another, you can use the average integral deviation of the conditional dynamic FLL from the conditional static:

$$\overline{M\left(P\right)-P}=\frac{1}{L_H}\left\{\int_0^{L_A}\left(M\left(P\right)-P\right)dL-\int_{L_A}^{L_H}\left(M\left(P\right)-P\right)dL\right\},$$

L_A – intersection point of graphs of conditional static and conditional dynamic FLL (Fig.2);

L_H – integration interval.

Dose values expressed in terms of D_{50}, in which the conditional static and conditional dynamic factorial laws of destruction are equal, can be determined by equating them to each other. Performing the necessary transformations, we get:

$$D_a=D_{50}e^{-\frac{1}{4K}\left[1+\sqrt{1+\frac{K}{K_n}}\right]},$$

whence it follows, two laws coincide at a certain dose value somewhat less than D_{50}.

In the future, using allowable measurement errors of ionizing radiation devices justified by the method considered, it is possible to introduce into consideration the indicators and criteria for the effectiveness for functioning of the radiation monitoring system.

To assess the degree of influence of radioactive contamination of the area on the livelihoods of the population, it is necessary to identify the radiation situation, that is, to determine the extent and degree of radioactive contamination of the area. The most thorough monitoring implies a further calculation of the synergistic effect of exposure [14].

Therefore, the ratio of the total area of a radioactively contaminated area identified during the monitoring to the area of the actually contaminated area can be considered as an indicator of the efficiency of the radiation monitoring system. This ratio of areas is in the interval [0.1] and is random in nature, since it depends on methods of conducting radiation monitoring of the area and indicators of the quality of devices.

By setting the criterion for the efficiency of the radiation monitoring system, for example, the expectation of a random variable — an area ratio indicator, the inverse problem can be solved. To substantiate the requirements for methods of conducting radiation monitoring at a given level of instrument quality indicators. On the contrary, for given methods of conducting radiation monitoring, to substantiate the requirements for instruments for measuring ionizing radiation according to the criteria of a higher level.

References

[1] "Sources of radioactive contamination of Techa River and the area of MAYAK plant, Ural, Russia", Joint Russian-Norwegian team of experts on radioactive contamination of northern lands. Osteras, Norway, 2000, p. 134. Retrieved from: www.feerc.ru/radsafety/Archive/PDF_ archive/.../Techa_Mayak/byVakulovsky.pdf (reference date 08.02.2019).

[2] E. Piesch, B. Burgkhardt, M. Vilgis, "Progress in Phosphate Glass Dosimetry: Experience and Routine Monitoring with Modern Dosimetry System", Radiat. Prot. Dosim., vol. 47, pp. 403–414, 1993.

[3] L. Struelens, F. Vanhavere, H. Bosmans, R. Van Loon, H. Mol, "Skin dose measurements on patients for diagnostic and interventional neuroradiology: a multicentre study", Radiation protection dosimetry, vol. 114, no. 1–3, pp. 143–146, 2005.

[4] V. Tasapaki, S. Kottou, E. Vano et al., "Patient dose value in a dedicated Greek cardiac center", Br. J. Radiol., vol. 76, pp. 726–730, 2003.

[5] D. Bor, S. Cekirge, T. Turkay, O. Turan, M. Gulay, E. Onal, B. Cil, “Patient and staff doses in interventional neuroradiology”, Radiat Prot Dosimetry, vol. 117 (1–3), no. 1, pp. 62–68, December 2005.

[6] K.F. Layton. D.F. Kalimes, H.J. Cloft, et al., “Radiation Exposure to the Primary Operator during Endovascular surgical neuro radiology procedures”, Am. J. Neuroradiol, vol. 27, pp. 7422–7430, 2006.

[7] S.V. Loginova, “Radiophotoluminescent method of measurement of a radiation background in atmospheric monitoring”, dis. of cand. of Phys. and Math. Sc. St. Petersburg, 2003, 125 p. Retrieved from: http://www.dissercat.com/content/radiofotolyuminestsentnyi-metod-izmereniya-radiatsionnogo-fona-v-monitoringe-atmosfery#ixzz52Sn AhvNk (reference date 08.02.2019).

[8] “Chernobyl heritage: Medical, ecological, social and economic repercussions along with recommendations to the governments of Belarus, Russia and Ukrain”, Chernobyl forum, 2003–2005, 2nd ed., revised. IAEA, Vienna, 2006. Retrieved from: http://www.who.int/ ionizing_radiation/chernobyl/ru/ (reference date 08.02.2019).

[9] A.A. Kokoshin, Notes on a problem of nuclear terrorism in modern world politics. Reflections about the book by G. Allison, “Nuclear Terrorism. In the end, an accident could be prevented”. Moscow: Editorial URSS, 2004.

[10] G.T. Allison, Nuclear Terrorism: The Ultimate Preventable Catastrophe. Moscow: LKI, 2007.

[11] L.K. Orlik, S.A. Semenov, S.V. Guseva, A.V. Kislyakov, A.P. Sholokhova, N.M. Kirsanov, Terrorism: problems, models, scenarios. Moscow, 2009.

[12] A.I. Kobzar, Applied mathematical statistics: for engineers and academic researchers. Moscow: FIZMATLIT, 2006.

[13] I. Kulikov, Applied statistical analysis: college-level study guide, 2nd ed., revis. and enlarg. Moscow: Goryachaya liniya-Telekom, 2008.

[14] L.K. Orlik, M.V. Faminskaya, N.S. Yushchenko, “Mathematical model of synergetic effect of radio nuclide impact on a biotarget”, Scholarly notes of Russian State Social University, no. 6 (62), pp. 168–172, 2008.