ISSN-L 2664-9969; E-ISSN 2706-5448

UDC 53.082.79:622.8:331.4:613.648.4
DOI: 10.15587/2706-5448.2024.319636

**Volodymyr Korotaev,
Anatolij Belikov,
Oleksandr Pylypenko,
Serhii Podkopaev,
Oleksandr Tkachuk,
Volodymyr Shalomov**

THEORETICAL AND PRACTICAL SUBSTANTIATION FOR PREDICTION OF EQUIVALENT DOSE RATE OF GAMMA RADIATION AT THE SUKHACHIVSKE TAILINGS STORAGE FACILITY I SECTION

The object of the study is the Sukhachivske industrial site, tailings storage facility section I (Ukraine). The main reason for conducting the study is to establish actual and forecast numerical values of absorbed and exposure dose rates. The state of radiation contamination of the tailing's storage facilities of the Sukhachivske industrial site was analyzed. The actual and prolonged levels of equivalent dose rate, absorbed dose rate, and total personnel exposure dose were determined. Dependencies were established that allow determining approximate numerical values for specific conditions and certain areas using the finite element method with subsequent transfer of values to 2024–2027. Based on the conducted studies, the dynamics of contamination at the Sukhachivske tailings storage facility section I was predicted. The estimated, forecast, and actual values of personnel exposure doses were determined for the period from 2010 to 2023. New methods and algorithms for instrumental measurement of radiation parameters at the tailing's facilities of the former uranium production facility of the Prydniprovsky Chemical Plant have been developed. The state of radiation contamination of the tailing's facilities of the Sukhachivke industrial site has been analyzed. The actual and prolonged levels of equivalent dose rate, absorbed dose rate, total personnel exposure dose, and contamination levels of the territories adjacent to the tailings facilities have been determined. Monitoring studies over ten years have allowed to determine the actual values of the exposure dose rate, which range from 0.08 to 0.21 μSv/h with certain local values up to 0.26 μSv/h. In general, the total personnel exposure dose does not exceed 1.1–1.4 mSv/year. The obtained data on prognostic values, in turn, make it possible to predict the further radiation situation at the Sukhachivske industrial site in the coming years. As well as to improve the system for calculating the total effective radiation dose, both to the personnel of the radiation-hazardous facility and to the population living near the industrial site.

Keywords: *measurement of parameters, tailings facility, radiation facility, radiation monitoring, γ-radiation, absorbed and exposure dose rates.*

Received: 11.10.2024
Received in revised form: 07.12.2024
Accepted: 19.12.2024
Published: 30.12.2024

How to cite
Korotaev, V., Belikov, A., Pylypenko, O., Podkopaev, S., Tkachuk, O., Shalomov, V. (2024). Theoretical and practical substantiation for prediction of equivalent dose rate of gamma radiation at the Sukhachivske tailings storage facility I section. Technology Audit and Production Reserves, 6 (2 (80)), 16–27. https://doi.org/10.15587/2706-5448.2024.319636

1. Introduction

The issue of radiation safety for Ukraine has arisen since the mid-1940s, with the beginning of the Soviet uranium enrichment program for the production of nuclear weapons. In accordance with the decision of the leaders of the union, it was decided to mine uranium ore in the city of Zhovti Vody, and organize the enrichment process at Plant 906 in the city of Kamianske (formerly Dniprodzerzhynsk). In the next fifty years, the Dnipropetrovsk region processed, enriched and accumulated radioactive substances, materials and waste. In the 70s, it was planned to build 8 nuclear power plants (NPPs) in Ukraine. Today, four nuclear power plants are operating in Ukraine, one of which is located in the occupied territory of the Zaporizhzhia region. After the start of a full-scale war, the issue of nuclear facilities and radiation-hazardous facilities (RHF) is one of the biggest problems for Ukraine, for our neighbors and for the entire European part of the continent, since RHF and NPPs operate and are operated under martial law.

Therefore, the operation of RHF, such as the tailings storage facilities of the former uranium production of the Prydniprovskyi Chemical Plant (PCP, Ukraine), is impossible without a system of territory protection, physical protection, radiation surveillance system. As well as systematic monitoring of the tailing's storage facility and control of radiation parameters in the adjacent territories.

Therefore, studies devoted to monitoring in radiation-contaminated territories of the nuclear fuel cycle (NFC) are relevant.

Radiation safety issues are important not only for Ukraine, but also for any corner of the world. Thus, in [1] the level of radioactive contamination of some basic food products in Mali was studied. The main food products for the inhabitants of Mali were identified and the content of radionuclides in milk, rice, sugar, wheat flour was calculated. Using gamma spectrometry, the researchers measured the activity concentration of radionuclides, such as uranium-238, thorium-232, potassium-40 and cesium-137, in 16 food samples collected from different locations in the city of Bamako, Mali. However, these studies concern the inhabitants of Mali and cannot be unambiguously used for Ukraine. That is, they do not address the issue of contamination of agricultural crops bordering the former uranium production in the Dnipropetrovsk region. The results showed relatively low levels of radioactivity, and the values of radiation hazard indices, such as the annual effective dose, were within the safe limits recommended by international standards, including those of the International Commission on Radiological Protection. This study adds to the body of research on food safety and radiological exposure, especially in regions where radionuclide contamination may be of concern due to environmental factors or agricultural practices.

Research [2] focuses on the radiological risks faced by people living near the Betare-Oy gold mining area. This area in Cameroon is known to have elevated levels of natural radiation due to the presence of radioactive minerals in the soil, which mining activities can release and disperse into the environment. The study shows that residents of these mining areas are exposed to increased levels of radon and other naturally occurring radioactive elements. One possible explanation for these adverse effects may be that the studies did not measure the equivalent dose rate or exposure dose rate. Local residents may be at higher risk of lung cancer as a result of long-term exposure to these radioactive materials, particularly through inhalation of radon gas, which is a known lung carcinogen. This assessment highlights the need for radiological safety measures and more comprehensive health monitoring for communities. The authors of the study emphasize the importance of implementing a set of protective measures to reduce risks, suggesting improving the level of waste management in the mining industry and making medical examinations of people regular for early detection of potential diseases. However, the study data do not address the issue of risk assessment for physical protection, security and radiation control personnel of the former uranium production of the "PCP".

In [3], the authors proposed approaches to increasing the efficiency of gamma-neutron shielding of polyvinylidene fluoride for high-power applications in the nuclear industry by incorporating tungsten compounds into polyvinylidene fluoride (PVDF). It was also analyzed how tungsten compounds affect its radiation shielding ability. This approach was applied by adding tungsten carbide (WC), tungsten trioxide (WO_3) and tungsten disulfide (WS_2) to PVDF and using tools such as EpiXS, Phy-X/PSD and MCNP5 to model the shielding effects. The findings show that PVDF with tungsten carbide (PVDF-xWC) was the most effective for both gamma and neutron radiation protection. The authors conducted a Monte Carlo simulation using MCNP5 software. The models confirmed that PVDF-xWC reduces the gamma dose rate more effectively than pure PVDF, highlighting its potential for improved radiation protection in nuclear applications. The proposed approaches are related to efficiency improvements in the nuclear industry, while the studies presented in the article concern industrial sites with radioactive waste in natural formations. However, these studies can be applied to the installation of protective screens around tailings facilities of former uranium production [3], which will solve the issue of reducing the total radiation dose for personnel.

A number of researchers have also been involved in modeling using the Monte Carlo method in the field of calculating organ radiation doses for patients undergoing medical diagnostic procedures [4]. Chinese researchers conducted Monte Carlo modeling in the study of individual variation in organ radiation doses during photon external irradiation [5]. The results of the presented studies of modeling processes in medicine and in personnel irradiation showed that the use of the Monte Carlo method has found its application in studies [6]: on determining exposure during 125I seed treatment using a thermoluminescent dosimeter based on a computational phantom. This methodological approach was applied in work [7] when calculating isotopes of a projectile from therapeutic carbon and helium ion beams in various materials. An option for further research may be systematic monitoring studies of the impact of increased radiation doses on personnel at industrial sites. However, it should be noted that the applied method was used for medical and agricultural research, while the article is devoted specifically to modeling processes in the conditions of an operating industrial site.

The authors analyzed the application of methods [8] to calculate the radiation dose of workers working in radiation-contaminated areas of the former uranium production of the Ukrainian State Chemical and Industrial Complex "PCP", taking into account the conducted full-scale experiment on a male dummy phantom Alderson-RANDO [9]. In these studies, a standard male phantom was analyzed, but physical protection workers working in tailings facilities have different anthropometric indicators (height, weight, age, etc.). The conducted experiment allowed to assess the impact of radiation on certain parts of the body and can be used for further studies of dose accumulation for people who have a "non-standard shape".

The most interesting scientific work for our research and further modeling was presented by a group of Japanese scientists in [10]. The authors have created a software package called SUMRAY, which includes versions of R and Python. This code aims to facilitate cancer risk assessment by incorporating uncertainty analysis related to radiation exposure. SUMRAY uses cancer risk models derived from the Lifespan Study (LSS) of Hiroshima and Nagasaki survivors, focusing on overall mortality and cancer incidence. The software takes into account different exposure scenarios and demographic factors such as age and sex.

In [10], the SUMRAY models were tested using the Radiation Risk Assessment Tool (RadRAT) and showed acceptable agreement within confidence intervals, demonstrating its reliability for cancer risk predictions. SUMRAY is also available as open-source software, which promotes transparency and allows other researchers to use and improve the tool.

An option for developing the modeling processes for determining radiation risks (RadRAT) presented in [10] may be one of the most productive directions. This is the

 ISSN-L 2664-9969; E-ISSN 2706-5448

development of a mathematical module for the ANSYS or Geant4 software package.

According to the Resolution of the Cabinet of Ministers of Ukraine No. 1030 of September 13, 2022, the identification of a high-risk facility is carried out in three stages [11]:

Stage I – compilation of a list of hazardous substances by individual names, classes of hazardous substances and hazard categories, which are placed on the RHF, according to the design and technical documentation. For radionuclides (class 7), the lowest threshold mass of hazardous substances is used during transportation, transportation and storage.

Stage II – list of production facilities, sites, separately located buildings, etc. containing hazardous substances is compiled.

Stage III – actual mass of hazardous radioactive substances is determined in each individual production unit and the total mass of hazardous substances is calculated separately for each individual name of hazardous substance; the total mass of hazardous substances is calculated.

According to the Resolution of the Cabinet of Ministers of Ukraine No. 1030 for storage facilities (tanks) – the total mass of hazardous substances that can be placed in them at the maximum permissible load in accordance with the design or technical documentation. This is due to the requirements of the sanitary rules and radiation safety standards of Ukraine and the recommendations of the International Commission on Radiation Safety.

Tailing's facilities and industrial sites with radiation-hazardous substances are classified as critical infrastructure facilities, according to the Resolution of the Cabinet of Ministers of Ukraine dated October 9, 2020 No. 1109, (as amended by the Resolution of the Cabinet of Ministers of Ukraine dated January 16, 2024 No. 48) [12]. This distribution refers to sector 1 (fuel and energy sector) subsector 6 (nuclear energy) with services:

- nuclear fuel production;
- operation of nuclear subcritical facilities, nuclear reactors, spent nuclear fuel storage facilities;
- extraction and processing of uranium raw materials, etc.

All this allows to state that it is advisable to conduct a study dedicated to radiation monitoring with systematic measurements of radiation parameters as the main (basic) method of research on such RHFs as tailings facilities.

In this work, the authors draw on the previous experience of the most significant publications of the International Commission on Radiological Protection (ICRP) regarding general research in the field of radiation safety and the modern model of the influence of radionuclides (RN) on the formation of the total radiation dose. The most significant and significant is Publication No. 60 [13], which was published in 1991 and was supplemented in 2007 by Publication No. 103 [14], which became a further development of the scientific and methodological basis for calculating radiation doses, risk modeling and damage assessment. Publication No. 103 of the ICRP introduced changes to the procedure for calculating the effective dose, expanded the list of organs and tissues included in the determination of the effective dose. The values of the weighting coefficients for organs and tissues and types of radiation were partially changed, and reference voxel phantoms of an adult conventional man were also regulated. Previously, the ICRP did not regulate a specific phantom for calculations. In practice, various mathematical models were used, such as hermaphroditic MIRD phantoms or phantoms of different ages for newborns, children under 5 years of age, adolescents and adults.

The most important, over the past five years, was the ICRP Publication No. 151 [15], because it proposed the use of updated biokinetic models for new radionuclides and for already studied ones, but under conditions of different forms of entry into the body. The models take into account how radionuclides move, accumulate and are excreted from the body. These models allow for a more accurate calculation of doses from internal exposure, which is critically important for occupational radiation protection.

Therefore, *the aim of research* is to monitor the values of the exposure dose rate (EDR) of gamma radiation in three stages. This will make it possible to conduct systematic monitoring of the tailings facility, within the framework of a targeted program with a minimum error in measuring radiation parameters (RP).

2. Materials and Methods

The object of research is the Sukhachivske tailings storage facility section I (Ukraine), the general view of which with a cross-section is presented in Fig. 1.

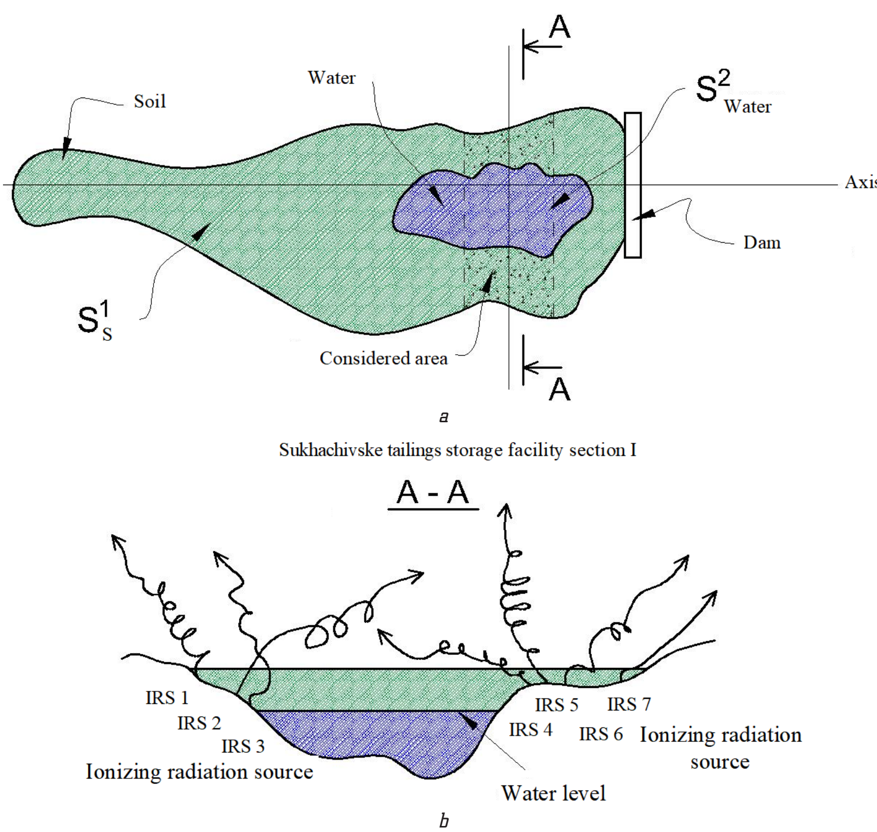

Fig. 1. 1st section of the Sukhachivske tailings storage facility:
a – general view; *b* – cross-section A–A in the selected segment of the considered area

Systematic measurements of absorbed dose rate (ADR), exposure dose rate (EDR) and beta particle flux density (FD) values were carried out on the perimeter of the RHF for ten years. The EDR values are presented in Table 1. The measurement data are recorded in the radiation monitoring reports on the perimeter of the Sukhachivske tailings facility section I for the period from 2011 to 2020.

Table 1

Data on γ-radiation EDR along the path of the work around the Sukhachivske tailings facility section I

Point No.	γ-radiation EDR during the years, μSv/h									
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020*
1	2	3	4	5	6	7	8	9	10	11
1	0.1	0.11	0.11	0.1	0.11	0.11	0.11	0.11	0.11	0.11
2	0.09	0.11	0.12	0.09	0.11	0.11	0.11	0.11	0.11	0.11
3	0.11	0.11	0.1	0.11	0.11	0.10	0.10	0.10	0.10	0.10
4	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
5	0.08	0.09	0.1	0.09	0.10	0.10	0.11	0.11	0.12	0.12
6	0.08	0.09	0.1	0.08	0.09	0.09	0.09	0.09	0.09	0.09
7	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
8	0.09	0.10	0.1	0.08	0.08	0.08	0.08	0.08	0.07	0.07
9	0.08	0.09	0.1	0.09	0.10	0.10	0.11	0.11	0.12	0.12
10	0.09	0.10	0.1	0.08	0.08	0.08	0.08	0.08	0.07	0.07
11	0.08	0.09	0.1	0.08	0.09	0.09	0.09	0.09	0.09	0.09
12	0.08	0.09	0.1	0.08	0.09	0.09	0.09	0.09	0.09	0.09
13	0.08	0.09	0.1	0.1	0.11	0.12	0.12	0.13	0.14	0.14
14	0.1	0.10	0.1	0.1	0.10	0.10	0.10	0.10	0.10	0.10
15	0.07	0.09	0.1	0.09	0.10	0.11	0.12	0.13	0.14	0.14
16	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
17	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
18	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
19	0.1	0.11	0.11	0.1	0.11	0.11	0.11	0.11	0.11	0.11
20	0.08	0.09	0.1	0.08	0.09	0.09	0.09	0.09	0.09	0.09
21	0.13	0.13	0.13	0.11	0.11	0.10	0.10	0.09	0.09	0.08
22	0.12	0.12	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.15
23	0.11	0.13	0.14	0.12	0.14	0.14	0.14	0.15	0.15	0.16
24	0.12	0.12	0.12	0.11	0.11	0.11	0.10	0.10	0.10	0.10
25	0.09	0.11	0.12	0.09	0.11	0.11	0.11	0.11	0.11	0.11
26	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.05	0.04	0.03
27	0.14	0.12	0.1	0.12	0.10	0.09	0.08	0.08	0.07	0.06
28	0.11	0.12	0.12	0.14	0.15	0.15	0.16	0.17	0.18	0.19
29	0.09	0.12	0.14	0.11	0.13	0.14	0.15	0.16	0.17	0.18
30	0.1	0.11	0.12	0.09	0.10	0.10	0.10	0.09	0.09	0.09
31	0.1	0.10	0.1	0.1	0.10	0.10	0.10	0.10	0.10	0.10
32	0.1	0.11	0.11	0.1	0.11	0.11	0.11	0.11	0.11	0.11
33	0.09	0.10	0.11	0.1	0.11	0.11	0.12	0.12	0.13	0.13
34	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.05	0.04	0.03
35	0.09	0.10	0.1	0.12	0.13	0.13	0.14	0.15	0.16	0.17
36	0.09	0.11	0.13	0.09	0.11	0.11	0.11	0.12	0.12	0.12
37	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
38	0.07	0.09	0.1	0.09	0.10	0.11	0.12	0.13	0.14	0.14
39	0.07	0.09	0.1	0.1	0.12	0.13	0.14	0.15	0.16	0.17
40	0.1	0.10	0.1	0.1	0.10	0.10	0.10	0.10	0.10	0.10
41	0.08	0.09	0.1	0.1	0.11	0.12	0.12	0.13	0.14	0.14
42	0.06	0.08	0.1	0.08	0.10	0.11	0.12	0.12	0.13	0.14
43	0.06	0.08	0.1	0.08	0.10	0.11	0.12	0.12	0.13	0.14
44	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
45	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
46	0.11	0.11	0.1	0.11	0.11	0.10	0.10	0.10	0.10	0.10
47	0.11	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12

Continuation of Table 1

1	2	3	4	5	6	7	8	9	10	11
48	0.15	0.13	0.11	0.11	0.09	0.08	0.06	0.05	0.03	0.02
49	0.12	0.12	0.12	0.15	0.15	0.16	0.17	0.18	0.19	0.20
50	0.11	0.13	0.15	0.12	0.14	0.15	0.15	0.16	0.16	0.17
51	0.11	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12
52	0.1	0.11	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13
53	0.14	0.13	0.11	0.1	0.08	0.07	0.06	0.04	0.03	0.02
54	0.13	0.12	0.1	0.14	0.13	0.13	0.13	0.13	0.13	0.13
55	0.13	0.14	0.15	0.13	0.14	0.14	0.14	0.14	0.14	0.15
56	0.14	0.14	0.13	0.14	0.14	0.13	0.13	0.13	0.13	0.13
57	0.15	0.15	0.14	0.15	0.15	0.14	0.14	0.14	0.14	0.14
58	0.14	0.15	0.14	0.13	0.15	0.13	0.14	0.16	0.13	0.15
59	0.12	0.15	0.17	0.12	0.15	0.15	0.15	0.15	0.15	0.16
60	0.1	0.12	0.13	0.1	0.12	0.12	0.12	0.12	0.12	0.12
61	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
62	0.12	0.12	0.11	0.12	0.12	0.11	0.11	0.11	0.11	0.11
63	0.11	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12
64	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
65	0.1	0.11	0.11	0.1	0.11	0.11	0.11	0.11	0.11	0.11
66	0.11	0.11	0.1	0.11	0.11	0.10	0.10	0.10	0.10	0.10
67	0.09	0.10	0.11	0.09	0.10	0.10	0.10	0.10	0.10	0.11
68	0.12	0.11	0.1	0.12	0.11	0.11	0.11	0.11	0.11	0.11
69	0.1	0.11	0.12	0.1	0.11	0.11	0.11	0.11	0.11	0.12
70	0.1	0.10	0.1	0.1	0.10	0.10	0.10	0.10	0.10	0.10
71	0.09	0.10	0.11	0.09	0.10	0.10	0.10	0.10	0.10	0.11
72	0.09	0.10	0.1	0.1	0.11	0.11	0.11	0.12	0.12	0.12
73	0.1	0.10	0.1	0.09	0.09	0.09	0.08	0.08	0.08	0.07
74	0.07	0.09	0.1	0.1	0.12	0.13	0.14	0.15	0.16	0.17
75	0.08	0.09	0.1	0.08	0.09	0.09	0.09	0.09	0.09	0.09
76	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
77	0.1	0.10	0.1	0.1	0.10	0.10	0.10	0.10	0.10	0.10
78	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
79	0.11	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12
80	0.09	0.10	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10
Average value	0.10	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.11	0.11

Calculated and field data on the measurements of γ-radiation EDR values collected at the Sukhachivske tailings facility section I were accumulated over thirteen years for the period 2008–2020, which is necessary for operational or emergency forecasting of the situation at the RHF and the formation of mathematical and calculation models. To form the database, the authors carried out preparatory work in the period from 2008 to 2010 on the collection of preliminary data for such parameters as the specific activity of the soils of the industrial site, equivalent, exposure and absorbed doses of radiation to personnel, equivalent equilibrium and volume activity of radionuclides. As a result of measurements of regulated parameters at the tailings storage facility of the Sukhachivske industrial site, the basic parameter for monitoring was determined – γ-radiation ADR and EDR. The authors carried out the main work on EDR measurements from 2011 to 2020, directly making measurements. Also, in the period from 2018 to 2020, the situation was simulated regarding the formation of equivalent and exposure doses of radiation, which were instrumentally (practically) confirmed during measurements of ADR and EDR, which were carried out by specialists of the radiation control service of the state enterprise (SE) "38 VITCH". Since 2020, the research object has been operating under quarantine restrictions and therefore access to the tailing's facility has been closed. Since February 24, 2022, martial law has been declared in Ukraine and access to the facility has been closed permanently. All data was collected during three stages of research at three locations of the Sukhachivske industrial site during 2011–2020:

– studies were conducted on the dam separating the first and second sections of the Sukhachivske tailings facility. The length of the section is approximately one and a half kilometers, where measurements were made at 15–23 points, depending on the year of the EDR measurements by walking gamma survey with an average step of 50 m;
– studies were conducted along the route from the dam around the Sukhachivske tailings facility section I. The length of the section is approximately 7500 m, where 80 measurements were made, with a step of approximately 75–100 m;
– studies were conducted around the Sukhachivske tailings facility section II. The length of the section

is approximately 5800 m, where 57 measurements were made, with a step of 75–100 m.

The measurements were carried out by foot survey, in search mode, while passing the measurement control points. Taking into account the obtained EDR data (Table 1) and the permissible total radiation dose for RHF personnel at the level of 2 mSv/year, operating conditions and type of tailings facility, in 2018 the authors calculated forecast data for the Sukhachivske tailings facility section I using the finite element method and the extrapolation method.

When conducting field radiation monitoring along the work path around the Sukhachivske tailings facility section I, the following instruments were used: gamma radiation dosimeter search DBG-01N No. 3933 and MKS-05 TERRA dosimeter-radiometer No. 11031013.

For each year, the average value was calculated taking into account data on the γ-radiation DER value separately for the study points on the dam and along the work path of the 1st and 2nd sections of the Sukhachivske tailings facility. Forecasted data for 2019–2023 were obtained by extrapolation and finite element method.

The RP determined in field conditions must be transferred to graphs for greater clarity. It should be noted that all modern calculations are based on the use of radiation characteristics of radionuclides presented in the fundamental provisions set out in ICRP Publication No. 38 and knowledge of radiation safety accumulated in ICRP Publication No. 60 [13]. Thus, ICRP Publication No. 116 "Coefficients for estimating quantities used in the field of radiological protection in external exposure of personnel" contains conversion factors for photons and electrons, which are doses per unit fluence of monoenergetic particles for 6 standard geometries of human body irradiation: anterior-posterior (AP), posterior-anterior (PA), right and left lateral (RLAT, LLAT), rotational (ROT) and isotropic (ISO), analyzed in previous studies [14].

3. Results and Discussions

Based on the recommendations of the ICRP on radiation monitoring of the RHF to determine the actual ranges of numerical fluctuations of the RP and to identify the dynamics of changes (↑↓) in the values of external exposure of the tailing's storage facility personnel. The results of field studies are presented for 2011–2017 in Fig. 2–8. The presented Fig. 2–8 show the actual distribution of ADR and EDR on the path of the work route used by workers, security guards and specialists of the enterprise.

Fig. 2–8 allowed to identify areas where the dynamics of growth or decrease in the values of the ADR and EDR are noticeable, and in some areas a stable picture without changes was revealed over a long period of observations. Based on the data obtained, it is possible to predict the values for the period from 2018 to 2029. Based on the results of the forecast, a graph was constructed with possible ADR and EDR levels for 2018–2020, in order to subsequently conduct measurements at the RHF and compare the data with those proposed in Fig. 9.

All data are grouped into a general Table 2.

It should be noted that the initial data of the anthropometry of the body of a worker at the RHF reflect, first of all, possible options for the exposure of a particular worker at a certain workplace. It is also necessary to take into account the conditions of exposure from the source (sources) of exposure concentrated in a certain location (for example, a single radiation source or a tailings storage facility). In existing software complexes (ANSYS, COMSOL Geant4, MCNP, etc.), external exposure from a radioactive cloud and from the deposition of radionuclides on the soil with rain is considered. Radiation dose estimates are performed for individual radionuclides and for certain IR distribution functions (Alfa, Beta, Gamma) for the ABS, EXP, LOG, TRG libraries.

In this regard, the use of external exposure coefficients for dose calculation is impractical, since it requires additional labor-intensive calculations, which does not correspond to the geometry of the exposure. Unlike the conversion factors presented in the ICRP Publications, the dose factors of the Oak Ridge National Laboratory [16, 17] are calculated separately for each of the 807 radionuclides and are the equivalent and effective dose rates from a unit concentration of the radionuclide in the environment.

One of the latest ICRP Publications No. 152 [18] "Radiation Damage Calculation Methodology" presents a new Concept of Radiation Damage for the quantitative assessment of the consequences of the stochastic effect from the exposure of the population to small doses or with a low dose rate. The effect is determined from the lifetime risks of cancer development and consequences for descendants, taking into account the severity.

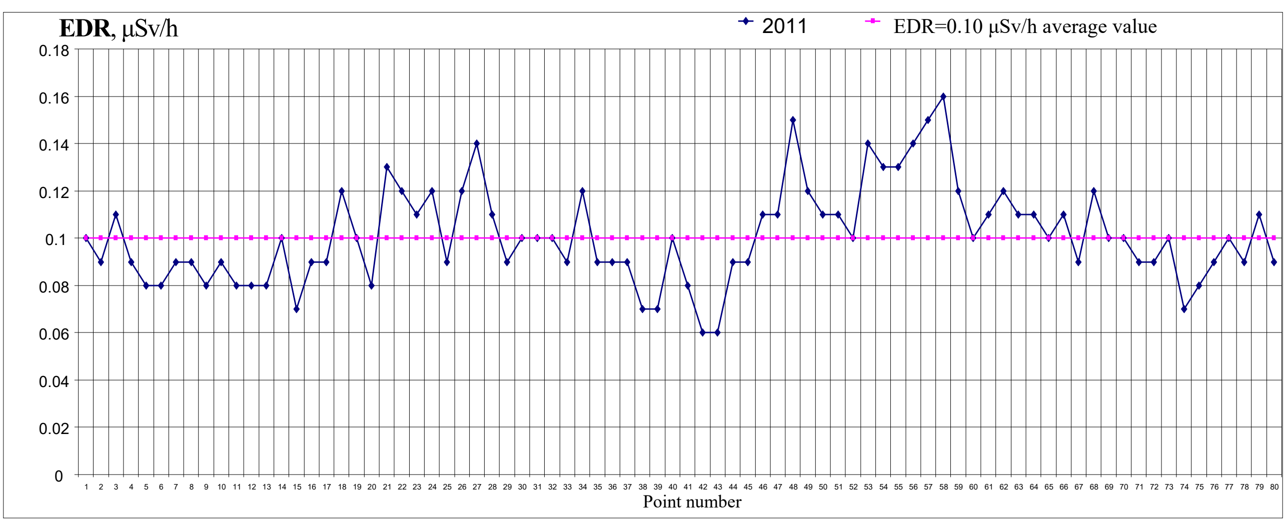

Fig. 2. Graph of γ-radiation exposure dose rate values around the Sukhachivske tailings facility section I for 2011

ISSN-L 2664-9969; E-ISSN 2706-5448

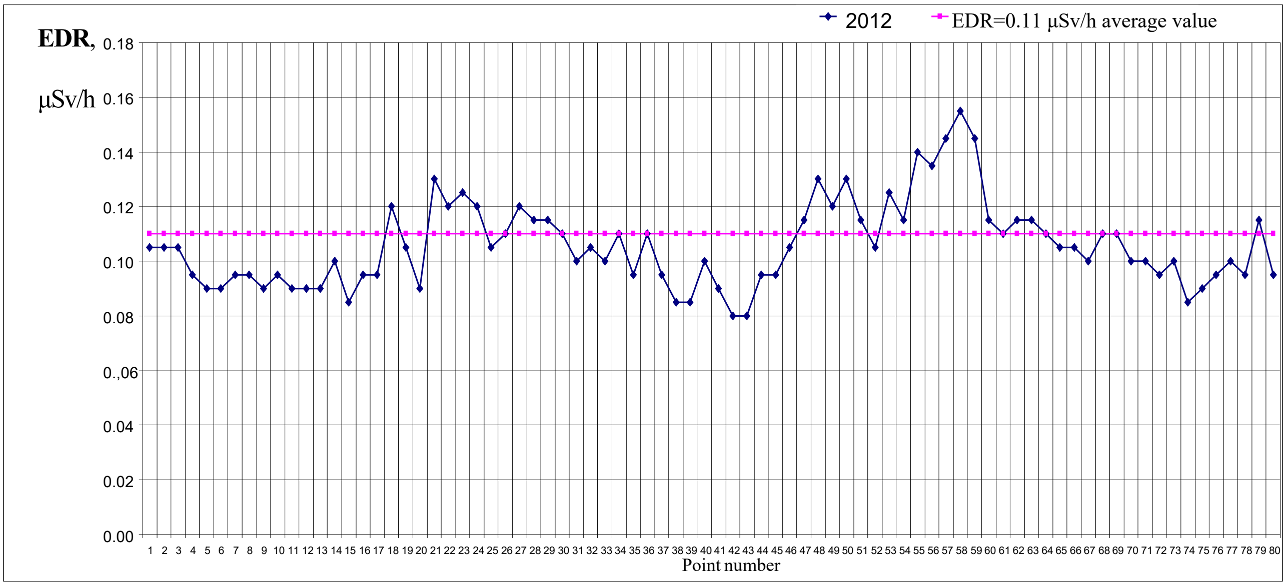

Fig. 3. Graph of γ-radiation exposure dose rate values around the Sukhachivske tailings facility section I for 2012

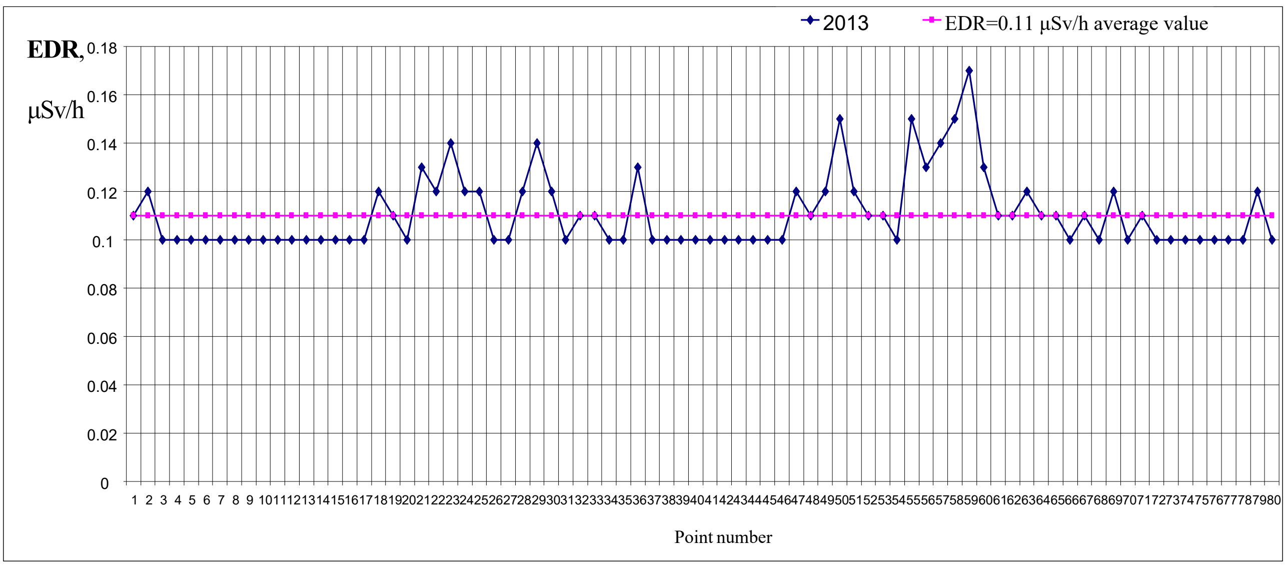

Fig. 4. Graph of γ-radiation exposure dose rate values around the Sukhachivske tailings facility section I for 2013

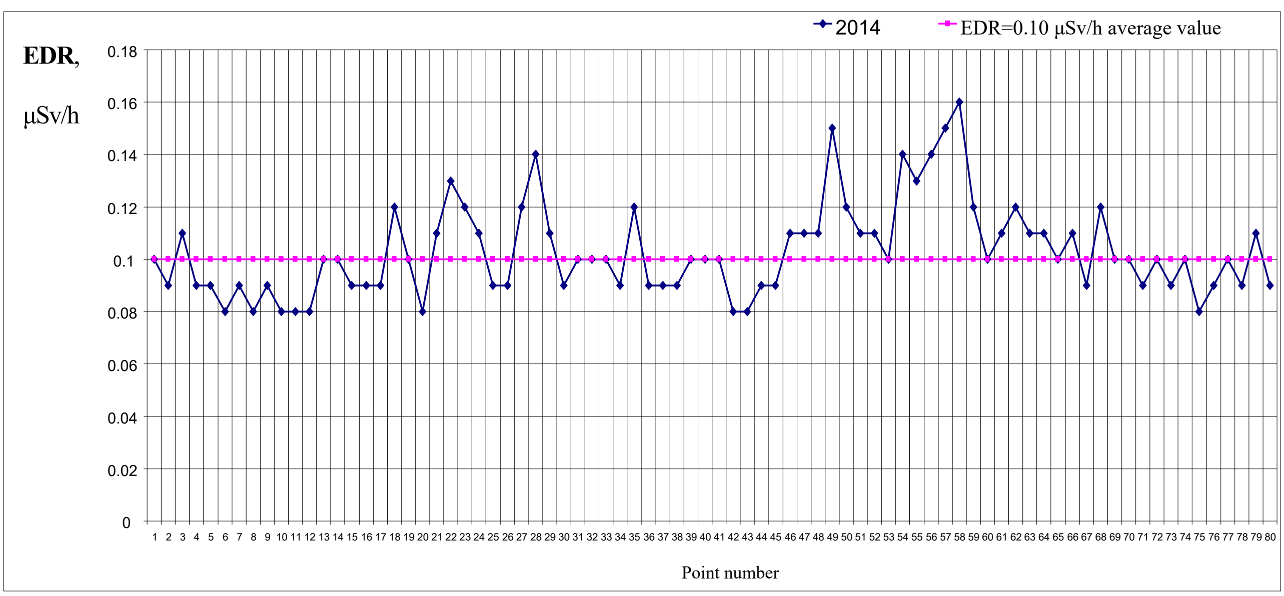

Fig. 5. Graph of γ-radiation exposure dose rate values around the Sukhachivske tailings facility section I for 2014

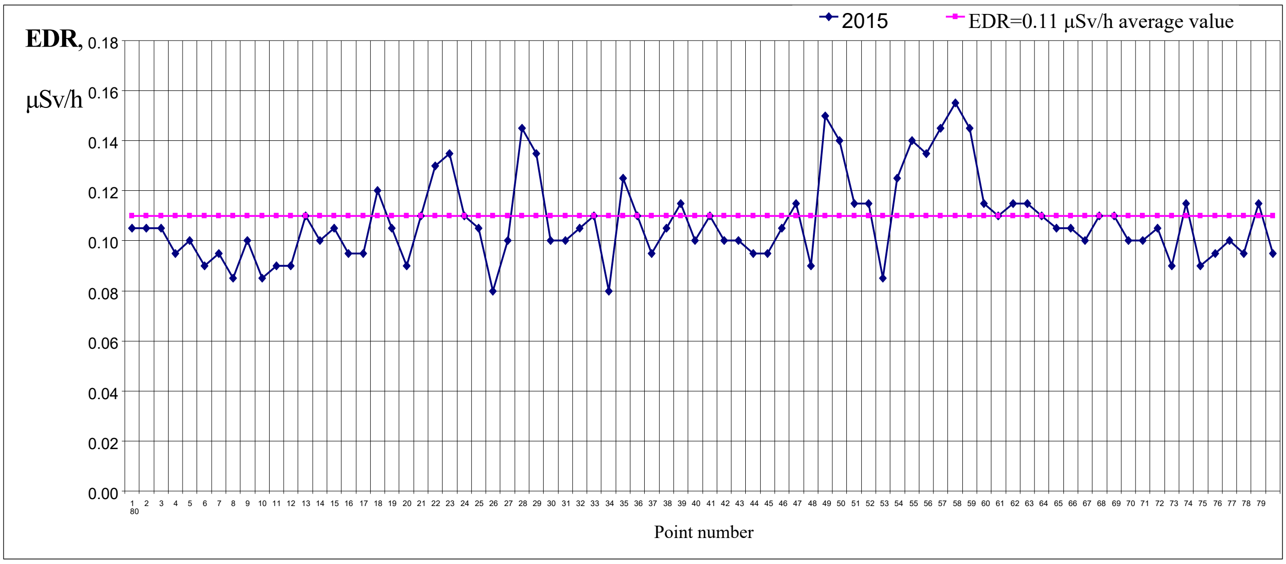

Fig. 6. Graph of γ-radiation exposure dose rate values around the Sukhachivske tailings facility section I for 2015

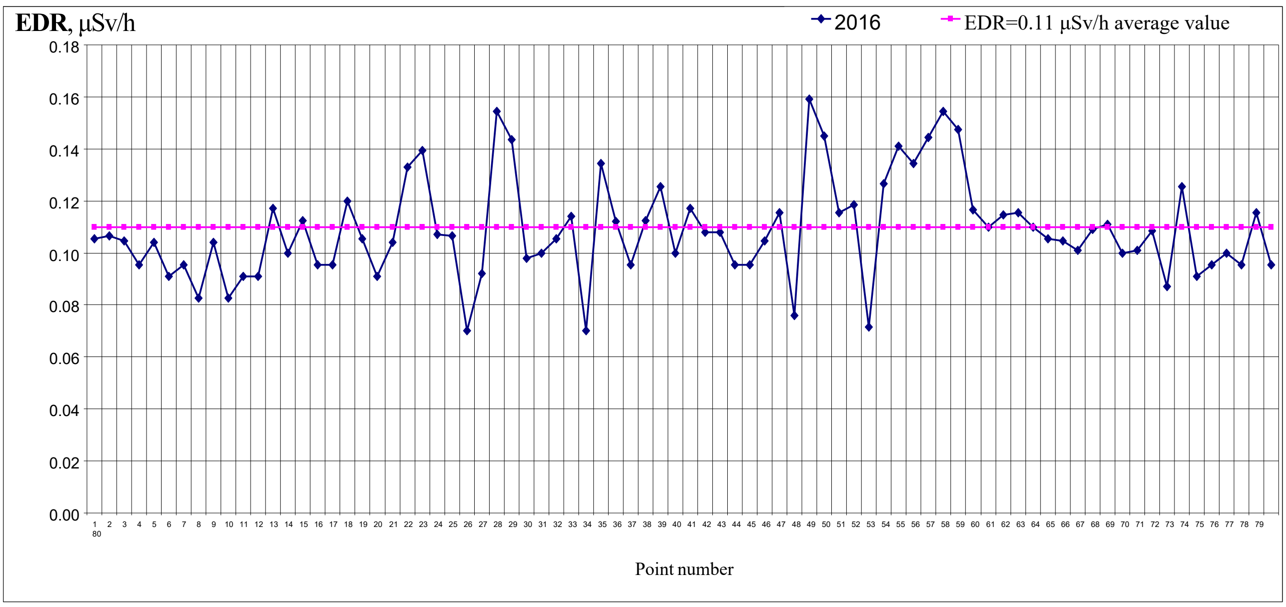

Fig. 7. Graph of γ-radiation exposure dose rate values around the Sukhachivske tailings facility section I for 2016

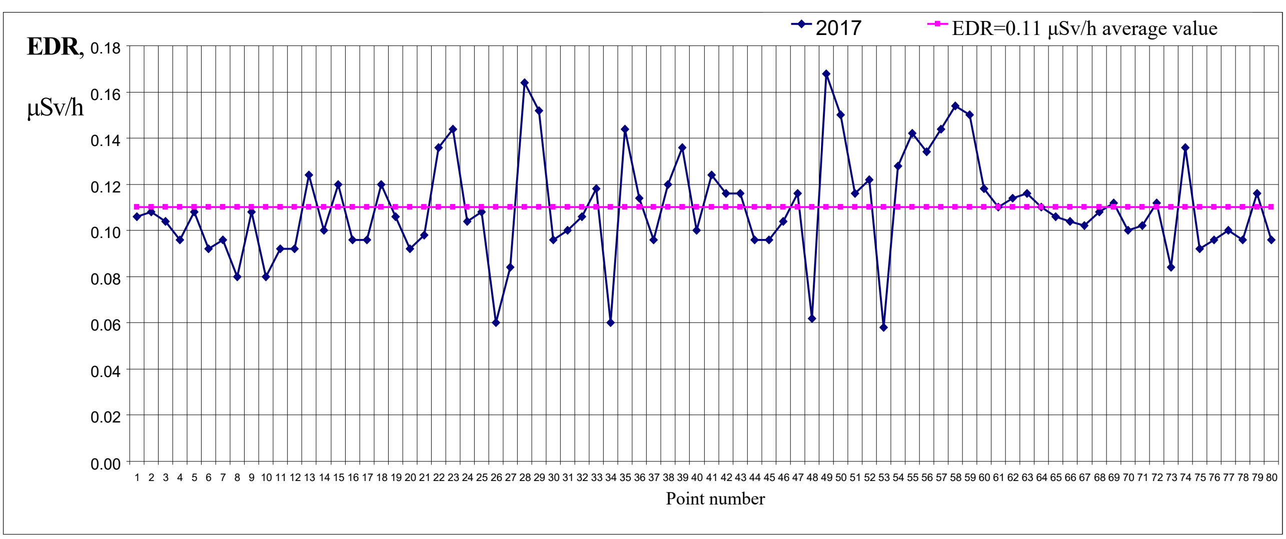

Fig. 8. Graph of γ-radiation exposure dose rate values around the Sukhachivske tailings facility section I for 2017

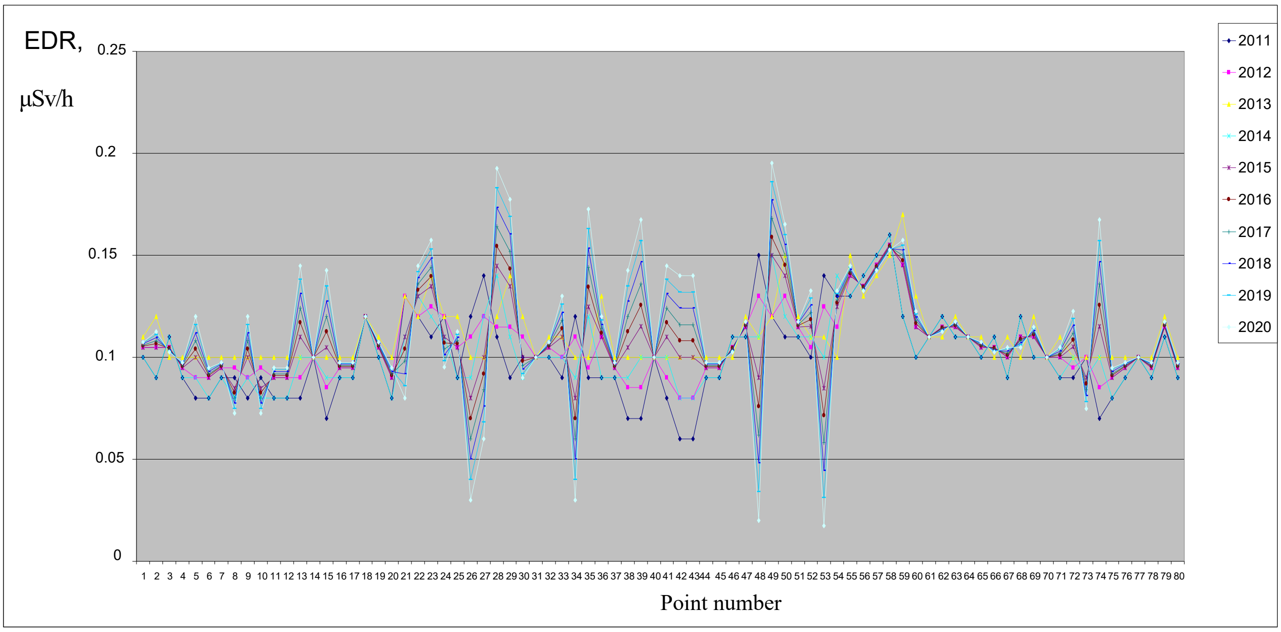

Fig. 9. Graph of γ-radiation exposure dose rates around the Sukhachivske tailings facility section I for 2011–2020

Table 2

Minimum and maximum γ-radiation EDR values at the study points along the working path around the Sukhachivske tailings facility section I for the period 2011–2020

Point No.	Minimum value (year), μSv/h	Maximum value (year), μSv/h	Dynamics of change in values	Difference between min and max, Δδ, μSv/h
1	2	3	4	5
1	0.10 (2011, 2014)	0.11 (2019)	No significant changes	0.01
2	0.09 (2011, 2014)	0.12 (2013)	No significant changes	0.03
3	0.10 (2013, 2016, 2019)	0.11 (2011, 2012, 2014)	No significant changes	0.01
4	0.09 (2011, 2014)	0.10	No significant changes	0.01
5	0.08 (2011)	0.12 (2019)	Increase	0.04
6	0.08 (2011, 2014)	0.10 (2012)	No significant changes	0.02
7	0.09 (2011, 2014)	0.10	No significant changes	0.01
8	0.07 (2019)	0.10 (2012, 2013)	Decrease	0.03
9	0.08 (2011)	0.12 (2019)	Increase	0.04
10	0.07 (2019)	0.10 (2012, 2013)	Decrease	0.03
11	0.08 (2011)	0.10 (2013)	No significant changes	0.02
12	0.08 (2011)	0.10 (2013)	No significant changes	0.02
13	0.08 (2011)	0.14 (2019)	Increase	0.06
14	0.10		Without changes	0.10
15	0.07 (2011)	0.14 (2019)	Increase	0.07
16	0.09 (2011, 2014)	0.10	No significant changes	0.01
17	0.09 (2011, 2014)	0.10	No significant changes	0.01
18	0.12		Without changes	0.12
19	0.10 (2011, 2014)	0.11	No significant changes	0.01
20	0.08 (2011, 2014)	0.10 (2013)	No significant changes	0.02
21	0.08 (2020)	0.13 (2011–2013)	Decrease	0.05
22	0.12 (2011–2013)	0.15 (2020)	Increase	0.03
23	0.11 (2011)	0.16 (2020)	Increase	0.05
24	0.10 (2017–2019)	0.12 (2011–2013)	Decrease	0.02
25	0.09 (2011, 2014)	0.12 (2011–2013)	No significant changes	0.03
26	0.03 (2020)	0.12 (2011)	Decrease	0.09
27	0.06 (2020)	0.14 (2011)	Decrease	0.08
28	0.11 (2011)	0.19 (2020)	Decrease	0.08
29	0.09 (2011)	0.18 (2020)	Increase	0.09
30	0.09 (2019)	0.12 (2013)	Decrease	0.03
31	0.10		Without changes	0.10

Continuation of Table 2

1	2	3	4	5
32	0.10 (2011, 2014)	0.11	No significant changes	0.01
33	0.09 (2011)	0.13 (2019)	Increase	0.04
34	0.03 (2020)	0.12 (2011)	Decrease	0.09
35	0.09 (2011)	0.17 (2020)	Increase	0.08
36	0.09 (2011)	0.13 (2013)	Increase	0.04
37	0.09 (2011, 2014)	0.10	No significant changes	0.01
38	0.07 (2011)	0.14 (2019)	Increase	0.07
39	0.07 (2011)	0.17 (2020)	Increase	0.10
40	0.10		Without changes	0.10
41	0.08 (2011)	0.14 (2019)	Increase	0.06
42	0.06 (2011)	0.14 (2020)	Increase	0.08
43	0.06 (2011)	0.14 (2020)	Increase	0.08
44	0.09 (2011, 2014)	0.10	No significant changes	0.01
45	0.09 (2011, 2014)	0.10	No significant changes	0.01
46	0.10	0.11	No significant changes	0.01
47	0.11 (2011, 2014)	0.12	No significant changes	0.01
48	0.02 (2020)	0.15 (2011)	Decrease	0.13
49	0.12 (2011, 2013)	0.20 (2020)	Increase	0.08
50	0.11 (2011)	0.17 (2020)	Increase	0.06
51	0.11 (2011, 2014)	0.12	No significant changes	0.01
52	0.10 (2011)	0.13 (2019)	Increase	0.03
53	0.02 (2020)	0.14 (2014)	Decrease	0.12
54	0.10 (2013)	0.14 (2011)	No significant changes	0.04
55	0.13 (2011, 2014)	0.15 (2013)	No significant changes	0.02
56	0.13 (2013)	0.14 (2012, 2015)	No significant changes	0.01
57	0.14	0.15	No significant changes	0.01
58	0.15	0.16	No significant changes	0.01
59	0.12 (2011, 2014)	0.17 (2013)	No significant changes	0.05
60	0.10 (2011, 2014)	0.13 (2013)	No significant changes	0.03
61	0.11		Without changes	0.11
62	0.11 (5 pcs.)	0.12 (4 pcs.)	No significant changes	0.01
63	0.11 (2011, 2014)	0.12	No significant changes	0.01
64	0.11		Without changes	0.11
65	0.10 (2011, 2014)	0.11	No significant changes	0.01
66	0.10	0.11	No significant changes	0.01
67	0.09 (2011, 2014)	0.11 (2013)	No significant changes	0.02
68	0.10 (2013)	0.12 (2011, 2014)	No significant changes	0.02
69	0.10 (2011, 2014)	0.12 (2013)	No significant changes	0.02
70	0.10		Without changes	0.10
71	0.09 (2011)	0.11 (2013)	No significant changes	0.02
72	0.09 (2011)	0.12 (2019)	Increase	0.03
73	0.07 (2020)	0.10 (2011)	Decrease	0.03
74	0.07 (2011)	0.17 (2020)	Increase	0.10
75	0.08 (2011)	0.10 (2013)	No significant changes	0.02
76	0.09 (2011, 2014)	0.10	No significant changes	0.01
77	0.10		Without changes	0.10
78	0.09 (2011, 2014)	0.10	No significant changes	0.01
79	0.11 (2011, 2014)	0.12	No significant changes	0.01
80	0.09 (2011, 2014)	0.10	No significant changes	0.01

The Publication presents a historical overview of the methodology for calculating such damage, starting with Publication No. 38, with a detailed description of the procedure developed in ICRP Publication No. 103 [14], which explains the sources for obtaining derived information, calculation methods and justification for the selection of significant parameters. The selected sensitivity analysis method for determining the parameters and calculation conditions that can be the main sources of variation and uncertainty in determining radiation damage showed that gender and age at the time of exposure, dose efficiency factor and its rate significantly affect the value of radiation damage. The current

ISSN-L 2664-9969; E-ISSN 2706-5448

model for calculating radiation damage needs to be developed by updating some parameters, such as information on the reference population and the severity of cancer cases, based on the latest epidemiological data.

The practical result of this study is the determination of the actual values of ADR and EDR at one of the tailings of the former uranium production of the "PCP", presented in Fig. 2–8. These data, which the authors collected over 13 years, allowed them to create a database of initial parameters, which in turn allowed them to forecast the radiation situation at the Sukhachivske tailings facility section I, which is reflected in Fig. 9.

The disadvantage of the proposed research method is the need to compare the data of field measurements with calculated ones. In addition, such research and forecasting process is not affected by weather indicators (temperature, pressure, wind speed, cold, etc.). This indicates the removal of radiation dust transport factors within the framework of a real research model.

In the future, it is proposed to use airborne remotely controlled devices to minimize the risks of radiation exposure of radiation control service personnel. In the future, it is necessary to continue improving research methods at the tailings of the former uranium production of the "PHP". Another mandatory area of research is the development of a modern updated regional or state methodology for measuring radiation parameters for monitoring radiation-contaminated areas. The results of these studies can also be used for other tailings dumps of the gully type.

One of the most productive areas is the development of a mathematical module for the ANSYS or Geant4 software package. This research also requires further development and analysis for mathematical forecasting, taking into account, within the framework of the developed module, the speed of air mass transport with radiation dust, under conditions of variations with variable factors, such as the type of RN, particle mass, concentration and accumulation of SRW in certain areas, etc.

4. Conclusions

Based on theoretical and instrumental studies, a scientific and practical justification was provided for determining the predicted values of ADR and EDR on the perimeter and inside the "body" of the Sukhachivske tailings facility section 1 (research period 2008–2020). The state of radiation contamination of the tailings facilities of the Sukhachivske industrial site was analyzed, the actual and prolonged levels of equivalent dose rate, absorbed dose rate, total personnel radiation dose and contamination levels of the territories adjacent to the tailings facilities were determined. This, in turn, makes it possible to predict the further radiation situation at the Sukhachivske industrial site in the coming years. During the measurements of EDR values, elevated levels were detected that were tied to a specific location relative to the tailing's facility bowl. Moreover, this trend began to be observed after 2015, in places where dusty particles from the RN settled on the leeward side in the summer and had annual confirmations in further forecasting and measurements as a result of a decrease in the surface of the tailings pond mirror.

The practical measurements and studies conducted by the authors allowed to detect stabilization of the EDR values on certain sections of the route of the Sukhachivske tailings facility section 1 of the "PCP".

Acknowledgements

The authors would like to express their gratitude to Oleksiy Kaplia – Deputy Director of the State Enterprise "38 VITCH" for initial professional training, retraining and advanced training in physical protection, radiation and chemical protection of fuel and energy complex facilities and labor protection for cooperation and support during the preparation of this article. His valuable ideas and contributions significantly improved the content presented in the article.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other nature, which could affect the research and its results presented in this article.

Financing

This article is a logical continuation of the scientific developments of the Department of Labor Protection, Civil and Technogenic Safety of the Ukrainian State University of Science and Technology, NSI "Prydniprovska State Academy of Civil Engineering and Architecture". The current scientific and research work is carried out according to the departmental theme "Occupational Protection, Industrial, Civil and Environmental Safety in Various Spheres of Human Life" No. State Registration 0124U001896 (in the period 2024–2026). This issue is of great importance for both the Dnipropetrovsk region and the state of Ukraine. There are about 42 million tons of solid and liquid radioactive waste from former uranium production at industrial sites.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the presented work.

References

1. Coulibaly, A., Kpeglo, D. O., Darko, E. O. (2023). Assessment of Radiological Hazards in Some Foods Products Consumed by the Malian Population Using Gamma Spectrometry. *Journal of Radiation Protection and Research, 48 (2),* 84–89. https://doi.org/10.14407/jrpr.2022.00178
2. Nkoulou, J. E. N., Engola, L. N., Dallou, G. B., Saïdou, Bongue, D., Hosoda, M. et al. (2023). Public Exposure to Natural Radiation and the Associated Increased Risk of Lung Cancer in the Betare-Oya Gold Mining Areas, Eastern Cameroon. *Journal of Radiation Protection and Research, 48 (2),* 59–67. https://doi.org/10.14407/jrpr.2021.00388
3. Ghazal, A. A., Alakash, R., Aljumaili, Z., El-Sayed, A., Abdel-Rahman, H. (2023). Enhancing Gamma-Neutron Shielding Effectiveness of Polyvinylidene Fluoride for Potent Applications in Nuclear Industries: A Study on the Impact of Tungsten Carbide, Trioxide, and Disulfide Using EpiXS, Phy-X/PSD, and MCNP5 Code. *Journal of Radiation Protection and Research, 48 (4),* 184–196. https://doi.org/10.14407/jrpr.2023.00213
4. Lee, C. (2024). A Review of Organ Dose Calculation Methods and Tools for Patients Undergoing Diagnostic Nuclear Medicine Procedures. *Journal of Radiation Protection and Research, 49 (1),* 1–18. https://doi.org/10.14407/jrpr.2023.00087

5. Lee, Y., Choi, J. W., Braunstein, L., Lee, C., Yeom, Y. S. (2024). Investigation on Individual Variation of Organ Doses for Photon External Exposures: A Monte Carlo Simulation Study. *Journal of Radiation Protection and Research, 49 (1),* 50–64. https://doi.org/10.14407/jrpr.2023.00661
6. Poorbaygi, H., Salimi, S. M., Torkzadeh, F., Hamidi, S., Sheibani, S. (2023). Determination of Exposure during Handling of 125I Seed Using Thermoluminescent Dosimeter and Monte Carlo Method Based on Computational Phantom. *Journal of Radiation Protection and Research, 48 (4),* 197–203. https://doi.org/10.14407/jrpr.2023.00255
7. Nizam, Q. M. R., Ahmed, A., Ahmed, I. (2023). Monte Carlo Calculation for Production Cross-Sections of Projectile's Isotopes from Therapeutic Carbon and Helium Ion Beams in Different Materials. *Journal of Radiation Protection and Research, 48 (4),* 204–212. https://doi.org/10.14407/jrpr.2023.00262
8. Pylypenko, O., Shalomov, V., Strezhekurov, Y., Rudenko, V., Tymchenko, P. (2024). The effect of external radiation exposure per person depending on his position and anthropometric indicators. *E3S Web of Conferences, 534,* 01016. https://doi.org/10.1051/e3sconf/202453401016
9. Bernhardsson, C. (2014). Experimental determination of dose conversion coefficients for external radiation exposure with gamma emitting radionuclides. *Radiatsionnaya Gygiena, 7 (4),* 125–133. Available at: https://lup.lub.lu.se/record/5048649
10. Sasaki, M., Furukawa, K., Satoh, D., Shimada, K., Kudo, S., Takagi, S. et al. (2023). SUMRAY: R and Python Codes for Calculating Cancer Risk Due to Radiation Exposure of a Population. *Journal of Radiation Protection and Research, 48 (2),* 90–99. https://doi.org/10.14407/jrpr.2022.00213
11. *Deiaki pytannia identyfikatsii obiektiv pidvyshchenoi nebezpeky* (2022). Postanova KMU No. 1030. 13.09.2022. Available at: https://www.kmu.gov.ua/npas/deiaki-pytannia-identyfikatsii-obiektiv-1030
12. *Deiaki pytannia obiektiv krytychnoi infrastruktury* (2024). Postanova KMU No. 1109. 09.10.2020. Available at: https://zakon.rada.gov.ua/laws/show/1109-2020-%D0%BF#Text
13. *ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1–3)* (1991). ICRP. Available at: https://www.icrp.org/publication.asp?id=icrp%20publication%2060
14. *ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2–4)* (2007). ICRP. Available at: https://www.icrp.org/publication.asp?id=ICRP%20Publication%20103
15. *ICRP, 2022. Occupational Intakes of Radionuclides: Part 5. ICRP Publication 151. Ann. ICRP 51 (1–2)* (2022). ICRP. Available at: https://www.icrp.org/publication.asp?id=ICRP%20Publication%20151
16. Trubey, D. K., Harima, Y. (1986). *New Buildup Factor Data for Point Kernel Calculations.* Technical Report. Oak Ridge National Lab. Available at: https://www.osti.gov/servlets/purl/6401756
17. Little, A., Piggott, M. D., Buchan, A. G. (2022). Development of a gamma ray dose rate calculation and mapping tool for Lagrangian marine nuclear emergency response models. *Marine Pollution Bulletin, 181,* 113895. https://doi.org/10.1016/j.marpolbul.2022.113895
18. *ICRP, 2022. Radiation detriment calculation methodology. ICRP Publication 152. Ann. ICRP 51(3)* (2022). ICRP. Available at: https://www.icrp.org/publication.asp?id=ICRP%20Publication%20152

Volodymyr Korotaiev, *PhD, Dnipro Scientific Research Forensic Centre of the Ministry of Internal Affairs of Ukraine, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0002-0269-0389*

Anatolii Bielikov, *Doctor of Technical Sciences, Department of Labor Protection, Civil and Technogenic Safety, Ukrainian State University of Science and Technologies, ERI "Prydniprovska State Academy of Civil Engineering and Architecture", Dnipro, Ukraine, ORCID: https://orcid.org/0000-0001-5822-9682*

Oleksandr Pylypenko, *PhD, Associate Professor, Department of Labor Protection, Civil and Technogenic Safety, Ukrainian State University of Science and Technologies, ERI "Prydniprovska State Academy of Civil Engineering and Architecture", Dnipro, Ukraine, ORCID: https://orcid.org/0009-0007-2987-7905*

Serhii Podkopaiev, *Doctor of Technical Sciences, Professor, Department of Mining Management and Labour Protection, Donetsk National Technical University, Lutsk, Ukraine, ORCID: https://orcid.org/0009-0002-6051-4719*

Oleksandr Tkachuk, *Chief Engineer, Structural Unit "Elektroremont" of PJSC "Donbasenergo", Mykolaivka, Donetsk region, Ukraine, ORCID: https://orcid.org/0000-0002-3129-2275*

✉***Volodymyr Shalomov,*** *PhD, Associate Professor, Department of Labor Protection, Civil and Technogenic Safety, Ukrainian State University of Science and Technologies, ERI "Prydniprovska State Academy of Civil Engineering and Architecture", Dnipro, Ukraine, e-mail: shalomov.volodymyr@pdaba.edu.ua, ORCID: https://orcid.org/0000-0002-6880-932X*

✉*Corresponding author*