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RADIATION HAZARD RESEARCH AT THE BASE-S INDUSTRIAL SITE USING MODELING

Purpose. To conduct comprehensive experimental studies at the industrial site of the former uranium production facility of the Prydniprovsky Chemical Plant and determine the value of the equivalent gamma dose rate to predict the dynamics of changes in radiation contamination at the "Base-S" industrial site.

Methodology. The theoretical, statistical, analytical and graphical modelling methods were used in the study with the use of 2D/3D models at nuclear fuel complex facilities, which include radiation-hazardous areas, burial sites, tailing pits and industrial sites with radioactive substances, materials or waste.

Findings. On the basis of the conducted research, the indicators of radiation contamination for the period 2009–2019 were determined. We developed and implemented 2D and 3D models for presenting the results obtained, with geolocation reference to each measurement point. Annual maps of radiation contamination were constructed, which allows forecasting the situation in the future. The maximum, minimum and average values for each section of the outfit path along which the facility personnel walk were determined, the dynamics of fluctuations in the equivalent dose rate was determined, additional studies were conducted on the required number of measurements to obtain the optimal time spent on the perimeter, and maps of radiation contamination of the industrial site were constructed.

Originality. For the first time, based on the data obtained, statistical and analytical processing of the results was carried out, taking into account the specifics of the developed two-dimensional or three-dimensional model, determining the data in clear space by approximating the linear function. The developed models implement the principle of adaptation of the obtained field measurement results and allow for a more accurate determination of the boundaries of radiation contamination zones at the industrial site through their visualization using 2D/3D models. Radiation risk parameters for the 'Base-S' industrial site were identified, and their temporal patterns and variations were analyzed, enabling a comprehensive approach to the implementation of radiation safety measures. For the first time, the developed 2D/3D models were applied, which correspond to the exact location of certain exposure zones. For greater visual perception of the model, it is proposed to represent different zones with four colours (from green to red), which allows determining the location and time of being in a certain location, on a given segment or in a certain zone of the "Base-S" industrial site.

Practical value. On the basis of the obtained experimental research, methodological recommendations for the implementation of new developments have been developed, improvement of the existing approaches of walking and remote sensing and implementation of modelling possible situations at radiation-contaminated sites. The built 2D/3D models allow us to assess the real situation at the industrial site over time and reduce the risk of additional exposure of personnel of the radiation-hazardous facility, the former uranium production facility of PChP located in the Dnipro region.

Keywords: *radiation hazard, dose, tailing dump perimeter, 2D/3D model, industrial site*

Introduction. Tailing dumps, industrial sites, sites with radiation residuals, nuclear fuel complex (NFC) facilities or other industrial or production facilities where solid/liquid radioactive waste (SRW/LRW) is collected, stored, and disposed represent a radiation danger to humans [1, 2]. The character of problems of radiation safety assurance demands a permanent system monitoring of the radiative and sanitary-and-hygienic parameters at the facilities of the former uranium production facility of PChP, located in the Dnipro region [3].

Literature review. The nuclear fuel complex of Ukraine began its development in the Dnipropetrovsk region. The uranium ore mining was produced at the newly established Vostochnyi Ore mining and processing plant in the town of Zhovti Vody on the border with the Kirovohrad region, enrichment of the obtained uranium ore was planned to be carried out at the newly built Plant 906 in the town of Dniprodzerzhynsk (today it is the town of Kamianske). On the border with the Kirovohrad region, the enrichment of the obtained uranium ore was planned to be carried out at the constructed Plant 906 in the city of Dniprodzerzhynsk (today it is the city of Kamianske).

In the period from the second half of the 1940s to the early 1990s, these two enterprises operated at full capacity, covering a requirement for enriched uranium for military and industrial (nuclear power plant) needs. At the start of 2025, Ukraine operates four nuclear power plants, including the Zaporizhzhia Nuclear Power Plant in the city of Enerhodar, which is situated in the temporarily occupied part of the Zaporizhzhia region. Since the start of the full-scale war, the safety of nuclear facilities and radiation-hazardous objects (RHOs) has become one of Ukraine's most critical challenges, as a number of RHOs and nuclear power plants continue to operate under martial law, posing serious risks to the environment and public health.

In the modern vision of climate change [4], risk factors [5], including radiation exposure of workers and personnel (ALARA principle – As Low As Reasonably Achievable), the nuclear fuel complex of Ukraine (NFC) [6, 7], which includes the mining industry, the mineral processing industry, nuclear technologies, the use of solid fuel elements in nuclear power plant reactors, the unloading of spent fuel, and the subsequent storage of solid/liquid radioactive waste at industrial sites [8, 9], can lay the groundwork for various types of accidents [10].

To prevent accidents at NFCs, such as nuclear power plants (NPPs), stationary automatic (semi-automatic) air, water, and soil monitoring systems are installed around them. The main causes of accidental releases at nuclear power plants [11] are mainly related to power supply systems, protective systems, malfunction of primary and secondary technological systems caused by overheating of the systems, increased pressure, or failure of certain safety systems (Fig. 1).

What is more, potential releases of radioactive material and accidents can occur in the mining industry during uranium ore extraction [12], but they are mainly incidental to the release of gaseous clouds with certain radionuclides.

As studies of the radiation background of housing have shown, an inhabitant of Ukraine, not related to the nuclear industry (NPP) or the mining industry (mines), who is staying in an ecologically safe area and a favorable natural environment, receives approximately 0.2–0.35 mSv/year (mainly in rural areas of the plain and steppe part of Ukraine); however, city residents living there receive approximately 0.25–0.6 mSv/year. It is important to note that in all possible accidents that occur at nuclear power plants and mining mines, the total amount of radiation contamination of the natural background does not exceed 1 and 0.5 %, respectively, which in total does not exceed 1.5 % of the total anthropogenic radiation background.

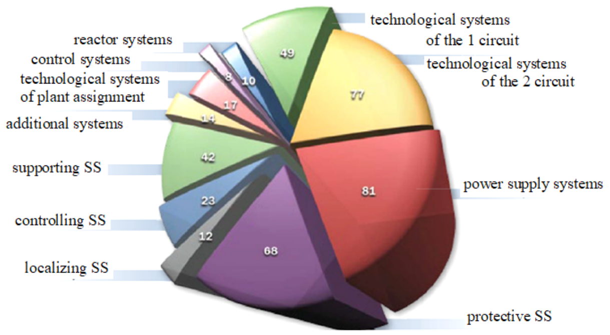

Fig. 1. Malfunctions (accidents) at nuclear power plants with possible release of radioactive material

One of the current ways of radiation exposure caused by radionuclide releases during the accident at the Fukushima-1 nuclear power plant [13] is inhalation of suspended 137Cs contained in the air. Although wind-induced resuspension of soil particles is recognized as the main mechanism of resuspension, research of the effects of the Fukushima-1 nuclear power plant accident has shown that bioaerosols may also be a potential source of atmospheric 137Cs in rural areas, although their quantitative impact on atmospheric 137Cs concentrations is still unknown. We propose a model for simulating the resuspension of 137Cs in the form of soil particles and bioaerosols in the form of fungal spores, which are considered as potential candidates for the role of a source of emissions of 137Cs-containing bioaerosols in the air.

Studies conducted by the authors [14] in June 2020 on observations of anthropogenic radionuclides in Estonia, Finland, and Sweden, which were not associated with any recognized release into the environment, led to a comprehensive investigation into the source and cause of the unusual releases. While aerosol sample analysis combined with atmospheric transport and dispersion modeling (ATDM) is a standard approach to studying particulate matter emissions into the environment, several new methods have been applied to better characterize the samples, allowing useful conclusions to be drawn. These conclusions were crucial for forming the final hypothesis regarding the type of object and the emission point.

Study [15] examines the radiological risks affecting populations residing in the vicinity of the Betare-Oya gold mining region. The findings indicate that this area of Cameroon is characterized by increased natural background radiation caused by radioactive minerals in the soil, which may be mobilized and spread into the environment as a result of mining operations. The results indicate that people living in these mining regions experience elevated exposure to radon and other naturally occurring radioactive substances. Prolonged exposure to these radioactive substances may increase the likelihood of lung cancer among local populations, particularly due to the inhalation of radon gas, which is a recognized carcinogen. This evaluation underscores the necessity of strengthening radiological protection measures and enhancing systematic health surveillance within affected communities. The study's authors stress the importance of adopting a comprehensive set of risk-mitigation actions, including improved waste management practices in the mining sector and the regular conduct of medical screenings to enable early detection of potential health disorders. However, these studies do not address the issue of risk assessment for physical protection, security, and radiation control of personnel of the former uranium production facility of PChP.

The authors [16] conducted a study (modeling) using the Monte Carlo method in the MCNP5 software environment. In the paper, the authors proposed approaches to increasing the gamma-neutron shielding efficiency of polyvinylidene fluoride for high-power applications in the nuclear industry by incorporating tungsten compounds into polyvinylidene fluoride (PVDF). Models confirmed that PVDF-xWC reduces gamma radiation dose rates more effectively than pure PVDF, highlighting its potential for improved radiation protection in nuclear programs. The proposed approaches are related to increasing efficiency in the nuclear industry, while the research presented in the article concerns industrial sites with radioactive waste in natural formations. The findings show that PVDF with tungsten carbide (PVDF-xWC) was the most effective for both gamma and neutron radiation protection. That is, these studies can be applied to the installation of protective screens around tailings facilities of former uranium production, which will solve the issue of reducing the total radiation dose for personnel.

Chinese researchers [17] conducted simulations by the Monte Carlo method to study individual variation of radiation doses on parts of the body during external photon irradiation. The quoted results of research on modeling processes in medicine and in personnel exposure showed that the use of the Monte Carlo method has found its application in studies [18] on determining the exposure of a thermoluminescent dosimeter based on a computational phantom. An option for further research could 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 existing industrial site.

The most similar studies were conducted in Ukraine, for the need to reevaluate the condition of lands outside the Chernobyl NPP exclusion zone. Thus, the authors of the study [19] on an experimental area of 100 hectares applied the method of quantitative determination of the density of 137Cs contamination by measuring the external dose, and the radionuclides 90Sr, 241Am, and 238Pu were quantitatively determined using selected soil samples. The authors conducted simulations by the Monte Carlo method to determine the potential exposure dose to agricultural workers. Based on statistical analysis of soil-plant concentration ratios, criteria were developed to assess the suitability of agricultural land for production. The authors also developed and built a 2D model indicating numerical data on external exposure, which made it possible to identify areas (regions) with an acceptable and increased level of equivalent radiation dose power for workers at the Base-S industrial site, which (level) affects the formation of the external component of the total radiation dose as a whole.

Unsolved aspects of the problem. The operation of radiation-hazardous facilities (RHF), such as the tailings dumps of the former uranium production of the Prydniprovsky Chemical Plant production enterprise, is impossible without a system of physical protection and radiation monitoring. The authors [20] set themselves the task of solving the issue of monitoring and determining the impact of external radiation on personnel in conditions where it is not possible to go directly to the industrial site and conduct full-scale measurements. For this purpose, mathematical forecasting methods were applied. Based on the conducted research, the dynamics of observations are calculated, and the predictive model allows determining regulated radiation parameters without using radiation monitoring devices, based on the database conducted in previous periods. To determine the situation in the future, a universal mathematical model was developed for determining the equivalent dose rate of gamma radiation to personnel with the ability to build a 2D model of the industrial site of the former uranium production facility of PChP. This makes it possible to predict the future radiation situation that will occur in the coming years and to improve the system for calculating the total effective radiation dose, both for the personnel of the radiation-hazardous facility and for the population living near the industrial site. For the construction of 2D maps, statistical data was collected at the "Base-S" tailings storage facility and the SE No. 6 storage facility, which belong to the radiation-contaminated territories of the former uranium production of the Pridneprovsky Chemical Plant near the settlement of Taromske. The method of squares, the method of foot video recording, was used, using interpolation, extrapolation, and least squares approximation. To construct 3D maps, a grid with a given cell size was defined, and cross-sections of 2D maps were constructed. Data measurements were carried out together with employees of the radiation monitoring service of the state enterprise SE "38 Viddil Inzhenerno-Tekhnichnykh Chastyn" for ten years (2009–2018). RRP measurements are performed using the method of walking or automobile gamma/beta survey with a certain selected measurement step or selected exposure, depending on the selected grid of points and measurement method.

Purpose (Objective statement and assignment of tasks). The aim of this study is to consolidate the findings of a comprehensive experimental investigation conducted at the industrial site of the former uranium production facility of the Prydniprovskyi Chemical Plant over the period 2008–2019, and to assess variations in the equivalent gamma radiation dose in order to forecast trends in radiation contamination at the 'Base-S' industrial site. To accomplish this objective, it is necessary to collect, process, and systematically analyze the relevant data "Industrial site – Source of radiation exposure – EDR value – Radiation dose"; to conduct a systematic analysis of research data; to determine the measurement step along the perimeter of the industrial site "Base-S"; to select and construct a grid of squares (square method); to build 2D/3D models of the industrial site; and to identify areas with certain levels of gamma radiation EDR that have an increased level of exposure from radioactive waste from the former uranium production facility of PChP.

Methodology. This study uses statistical and analytical methods [21] based on the fundamental principles of radiation exposure of personnel using the theory of radioactivity decay during the movement and accumulation of dust particles on the surface of tailing dumps without the use of a shield. Additionally, field (experimental) studies of changes in regulated radiation parameters were conducted, with modeling of situations and construction of 2D and 3D maps of radiation contamination of the industrial site.

The RRP survey was conducted using a gamma-beta radiation dosimeter-radiometer by MKS-07 "POSHUK" search, using a rod and two gamma and beta detection units [22]. The measurement error of the device is ±12–15 %, the wind speed is in the range from 0.8 to 2.9, and the atmospheric stability category is inversion at temperatures above 0 °C, in the absence of fog, rain, hail, in the period from March to November.

Considering that it is desirable to conduct measurements in dry and rainless weather, the most suitable conditions were selected for conducting systematic measurements to reduce the error and for the purity of the experiment.

Results/Presentation of basic material of the research. This paper presents a study of changes in the RRP of beta particle flux density and equivalent dose rate (EDR) of gamma radiation, which were conducted over a ten-year period from 2009 to 2018 (Table 1). As a result, actual field measurements were obtained on the trail along the perimeter of the Base-S industrial site, and processing the results allows you to determine the convergence of data in all areas of the radiation-hazardous facility, that is, the collected material can later serve as a database for planning and modeling the situation. For the research, areas were selected near the settlements of Svitle, Tytorov, Taromske, Sukhachivka, and Karnaukhovka, near which the research object is located – the Base-S" industrial site, where two RHOs were designed and where elevated levels of gamma radiation from industrial SRWs were recorded (Fig. 2).

At the primary stage, to conduct field measurements and further data processing, it was necessary to determine a measurement grid (square method) to most accurately reflect the research requirements. It was proposed to divide the industrial site into squares of 50 × 50 meters (Fig. 3) and squares of 100 × 100 meters (Fig. 4), and the measurement step for this grid was ≈ 20 meters to determine the EDR on the perimeter of the industrial site "Base-S". This division system was used for 3 years, in the period 2009–2011, the values for the 2009 research year are presented as an example.

At the secondary stage, to conduct field measurements and further data processing, it was necessary to determine a measurement grid to most accurately reflect the research requirements. It was proposed to divide the industrial site into squares of 50 × 50 meters (Fig. 5) and squares of 100 × 100 meters (Fig. 6), and the measurement step of values ≈ 40 meters to determine the EDR on the perimeter of the industrial site "Base-S". This system of dividing into squares and the chosen step were used for 7 years, in the period 2013–2019, the values for the 2015 research year are presented as an example.

Data on EDR of the γ-radiation along the path of the line around the industrial site "Base-S" (125 measurement points).

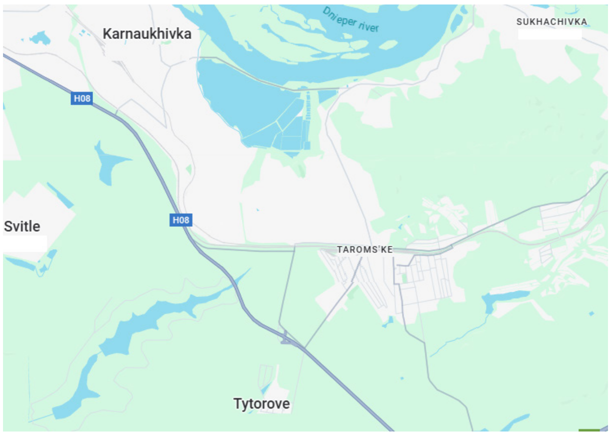

Fig. 2. The research site on the map of Ukraine (image from Google Earth)

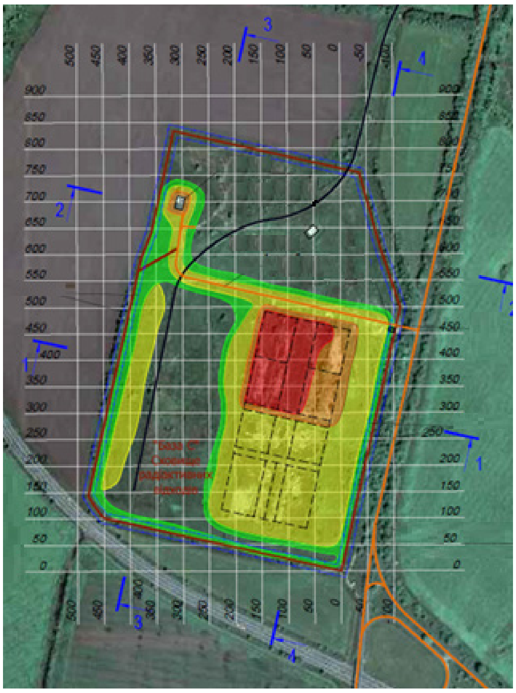

Fig. 3. Modifications of modeling the situation in 2009 at the "Base-S" industrial site for research in the period from 2009 to 2011 and construction of 2-D model map with a grid size of 50 × 50 meters

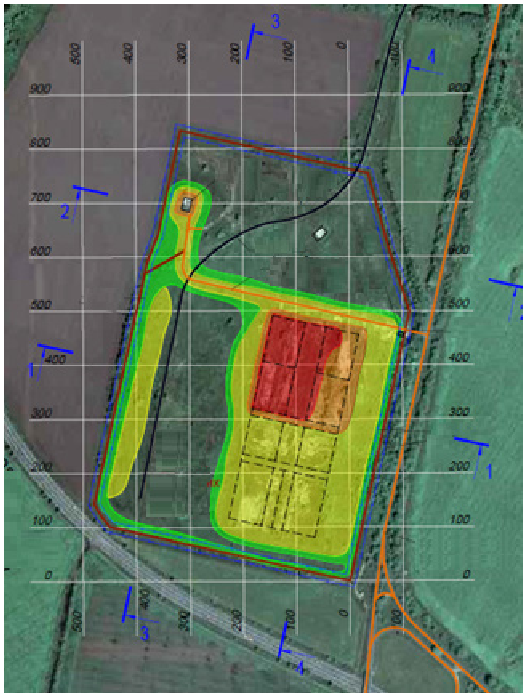

Fig. 4. Modifications of modeling the situation in 2009 at the "Base-S" industrial site for research in the period from 2009 to 2011 and construction of 2-D model map with a grid size of 100 × 100 meters

Based on the obtained data, statistical and analytical processing was carried out, taking into account the specifics of the developed three-dimensional model, determining data in clear space by approximating a linear function, obtaining data by interpolation method along the path of the work, and obtaining values by extrapolation in the middle of the "Base-S" industrial site and along its perimeter.

Table 1

Data on EDR of the γ-radiation along the path of the line around the industrial site "Base-S" (125 measurement points)

Point number	EDR γ-radiation by year, μSv/h			Point number	EDR γ-radiation by year, μSv/h					
	2009	2010	2011		2013	2014	2015	2017	2018	2019
Auto barrier	0.289	0.289	0.277	Auto barrier	0.283	0.281	0.27	0.277	0.281	0.275
1	0.264	0.267	0.278	–	–	–	–	–	–	–
2	0.269	0.238	0.244	1 (2)	0.26	0.245	0.252	0.261	0.244	0.251
3	0.183	0.183	0.181	–	–	–	–	–	–	–
4	0.164	0.164	0.166	2 (4)	0.16	0.162	0.151	0.158	0.159	0.152
5	0.183	0.171	0.174	–	–	–	–	–	–	–
6	0.170	0.179	0.168	3 (6)	0.18	0.171	0.169	0.168	0.16	0.163
7	0.163	0.158	0.163	–	–	–	–	–	–	–
8	0.158	0.158	0.15	4 (8)	0.15	0.158	0.132	0.14	0.137	0.138
9	0.121	0.133	0.122	–	–	–	–	–	–	–
10	0.126	0.136	0.128	5 (10)	0.13	0.13	0.124	0.14	0.134	0.133
11	0.111	0.123	0.12	–	–	–	–	–	–	–
12	0.13	0.137	0.131	6 (12)	0.132	0.13	0.124	0.121	0.121	0.12
13	0.254	0.269	0.263	–	–	–	–	–	–	–
14	0.214	0.218	0.216	7 (14)	0.208	0.2	0.211	02	0.221	0.21
15	0.232	0.23	0.237	–	–	–	–	–	–	–
16	0.368	0.408	0.389	8 (16)	0.36	0.35	0.348	0.31	0.281	0.264
railway gate	0.375	0.389	0.373	railway gate	–	–	–	–	–	–
17	0.268	0.259	0.262	9 (17)	0.252	0.25	0.241	0.244	0.24	0.242
18	0.224	0.209	0.214	–	–	–	–	–	–	–
19	0.193	0.191	0.19	10 (19)	0.197	0.193	0.19	0.188	0.191	0.187
20	0.136	0.144	0.142	–	–	–	–	–	–	–
21	0.124	0.138	0.12	11 (21)	0.124	0.126	0.118	0.127	0.119	0.121
22	0.126	0.126	0.126	–	–	–	–	–	–	–
23	0.133	0.122	0.128	12 (23)	0.13	0.134	0.124	0.128	0.135	0.14
24	0.136	0.124	0.122	–	–	–	–	–	–	–
25	0.148	0.138	0.131	13 (25)	0.132	0.127	0.128	0.137	0.123	0.125
26	0.199	0.18	0.163	–	–	–	–	–	–	–
27	0.196	0.178	0.187	14 (27)	0.174	0.159	0.16	0.178	0.177	0.171
28	0.196	0.18	0.178	–	–	–	–	–	–	–
29	0.193	0.178	0.179	15 (29)	0.181	0.184	0.185	0.176	0.176	0.181
30	0.149	0.149	0.141	–	–	–	–	–	–	–
31	0.188	0.193	0.172	16 (31)	0.171	0.195	0.179	0.18	0.168	0.16
32	0.125	0.137	0.12	–	–	–	–	–	–	–
33	0.196	0.172	0.191	17 (33)	0.184	0.181	0.178	0.187	0.173	0.173
34	0.199	0.18	0.165	–	–	–	–	–	–	–
35	0.162	0.162	0.167	18 (35)	0.163	0.163	0.164	0.158	0.161	0.17
36	0.196	0.174	0.202	–	–	–	–	–	–	–
37	0.202	0.188	0.208	19 (37)	0.21	0.182	0.177	0.189	0.181	0.18
38	0.286	0.284	0.274	–	–	–	–	–	–	–
39	0.279	0.27	0.288	20 (39)	0.287	0.27	0.249	0.23	0.239	0.227
40	0.264	0.26	0.261	–	–	–	–	–	–	–
41	0.288	0.302	0.292	21 (41)	0.278	0.262	0.257	0.243	0.244	0.25
42	0.262	0.224	0.251	–	–	–	–	–	–	–
43	0.198	0.21	0.211	22 (43)	0.19	0.188	0.191	0.192	0.187	0.19
44	0.204	0.214	0.211	–	–	–	–	–	–	–
45	0.214	0.218	0.218	23 (45)	0.208	0.222	0.207	0.221	0.218	0.204
46	0.268	0.252	0.26	–	–	–	–	–	–	–
47	0.247	0.255	0.239	24 (47)	0.251	0.27	0.258	0.274	0.263	0.256
48	0.24	0.234	0.234	–	–	–	–	–	–	–
49	0.266	0.26	0.242	25 (49)	0.265	0.266	0.26	0.268	0.241	0.265
50	0.256	0.26	0.254	–	–	–	–	–	–	–
51	0.381	0.392	0.377	26 (51)	0.382	0.381	0.374	0.309	0.275	0.286
52	0.402	0.41	0.411	–	–	–	–	–	–	–

Continuation of Table 1

Point number	EDR γ-radiation by year, μSv/h			Point number	EDR γ-radiation by year, μSv/h					
	2009	2010	2011		2013	2014	2015	2017	2018	2019
53	0.318	0.328	0.328	27 (53)	0.308	0.337	0.341	0.384	0. 347	0.382
54	0.281	0.277	0.27	–	–	–	–	–	–	–
55	0.44	0.412	0.421	28 (55)	0.417	0.414	0.41	0.4	0.405	0.415
56	0.268	0.284	0.281	–	–	–	–	–	–	–
57	0.326	0.333	0.331	29 (57)	0.338	0.314	0.326	0.338	0.344	0.374
58	0.273	0.266	0.27	–	–	–	–	–	–	–
59	0.268	0.282	0.262	30 (59)	0.28	0.272	0.274	0.268	0.275	0.266
60	0.253	0.264	0.271	–	–	–	–	–	–	–
61	0.194	0.197	0.183	31 (61)	0.192	0.171	0.18	0.198	0.219	0.208
62	0.182	0.207	0.217	–	–	–	–	–	–	–
63	0.378	0.385	0.327	32 (63)	0.34	0.36	0.318	0.312	0.338	0.303
64	0.181	0.177	0.187	–	–	–	–	–	–	–
65	0.139	0.128	0.141	33 (65)	0.141	0.141	0.129	0.141	0.127	0.158
66	0.204	0.178	0.186	–	–	–	–	–	–	–
67	0.187	0.207	0.188	34 (67)	0.193	0.214	0.203	0.19	0.198	0.184
68	0.191	0.209	0.19	–	–	–	–	–	–	–
69	0.175	0.175	0.175	35 (69)	0.177	0.175	0.171	0.221	0.211	0.189
70	0.171	0.166	0.164	–	–	–	–	–	–	–
71	0.158	0.138	0.129	36 (71)	0.15	0.144	0.153	0.148	0.154	0.151
72	0.166	0.148	0.187	–	–	–	–	–	–	–
73	0.174	0.18	0.179	37 (73)	0.79	0.166	0.168	0.18	0.169	0.176
74	0.174	0.159	0.143	–	–	–	–	–	–	–
75	0.204	0.188	0.202	38 (75)	0.182	0.174	0.17	0.193	0.207	0.194
76	0.193	0.169	0.184	–	–	–	–	–	–	–
77	0.163	0.175	0.165	39 (77)	0.154	0.16	0.142	0.144	0.187	0.154
78	0.158	0.153	0.155	–	–	–	–	–	–	–
79	0.187	0.19	0.212	40 (79)	0.193	0.177	0.17	0.18	0.203	0.186
80	0.173	0.174	0.186	–	–	–	–	–	–	–
81	0.143	0.143	0.15	41 (81)	0.155	0.154	0.153	0.143	0.147	0.158
82	0.158	0.156	0.15	–	–	–	–	–	–	–
83	0.198	0.202	0.208	42 (83)	0.207	0.202	0.199	0.185	0.2	0.97
84	0.196	0.178	0.191	–	–	–	–	–	–	–
85	0.226	0.242	0.242	43 (85)	0.241	0.268	0.273	0.248	0.28	0.274
86	0.238	0.257	0.247	–	–	–	–	–	–	–
87	0.38	0.392	0.388	44 (87)	0.348	0.312	0.367	0.342	0.321	0.333
88	0.294	0.28	0.273	–	–	–	–	–	–	–
89	0.287	0.268	0.28	45 (89)	0.278	0.287	0.281	0.316	0.283	0.29
90	0.276	0.261	0.282	–	–	–	–	–	–	–
91	0.316	0.358	0.378	46 (91)	0.363	0.378	0.341	0.311	0.32	0.35
92	0.308	0.388	0.371	–	–	–	–	–	–	–
93	0.369	0.408	0.428	47 (93)	0.402	0.42	0.408	0.398	0.412	0.4
94	0.411	0.43	0.421	–	–	–	–	–	–	–
95	0.438	0.441	0.42	48 (95)	0.401	0.43	0.413	0.42	0.418	0.408
96	0.486	0.48	0.464	–	–	–	–	–	–	–
97	0.407	0.426	0.438	49 (97)	0.417	0.39	0.408	0.39	0.374	0.38
98	0.292	0.351	0.332	–	–	–	–	–	–	–
99	0.284	0.268	0.278	50 (99)	0.303	0.299	0.282	0.3	0.274	0.26
100	0.263	0.277	0.281	–	–	–	–	–	–	–
101	0.271	0.269	0.293	51 (101)	0.307	0.285	0.277	0.27	0.266	0.25
102	0.264	0.302	0.287	–	–	–	–	–	–	–
103	0.287	0.314	0.32	52 (103)	0.29	0.288	0.294	0.281	0.268	0.266
104	0.294	0.387	0.331	–	–	–	–	–	–	–
105	0.426	0.4	0.443	53 (105)	0.412	0.412	0.407	0.4	0.395	0.388
106	0.486	0.511	0.494	–	–	–	–	–	–	–
107	0.49	0.516	0.507	54 (107)	0.481	0.465	0.43	0.431	0.42	0.41
108	0.417	0.408	0.403	–	–	–	–	–	–	–

End of Table 1

Point number	EDR γ-radiation by year, μSv/h			Point number	EDR γ-radiation by year, μSv/h					
	2009	2010	2011		2013	2014	2015	2017	2018	2019
109	0.389	0.4	0.376	55 (109)	0.39	0.402	0.397	0.38	0.385	0.39
110	0.208	0.269	0.231	–	–	–	–	–	–	–
111	0.276	0.272	0.271	56 (111)	0.284	0.267	0.268	0.267	0.277	0.271
112	0.273	0.27	0.286	–	–	–	–	–	–	–
113	0.268	0.266	0.254	57 (113)	0.256	0.25	0.261	0.25	0.248	0.261
114	0.26	0.271	0.29	–	–	–	–	–	–	–
115	0.29	0.299	0.311	58 (115)	0.308	0.306	0.3	0.292	0.273	0.281
116	0.291	0.315	0.302	–	–	–	–	–	–	–
117	0.268	0.297	0.283	59 (117)	0.288	0.28	0.28	0.274	0.26	0.263
118	0.273	0.288	0.292	–	–	–	–	–	–	–
119	0.284	0.278	0.28	60 (119)	0.271	0.279	0.281	0.27	0.272	0.265
120	0.261	0.287	0.275	–	–	–	–	–	–	–
121	0.289	0.289	0.267	61 (121)	0.263	0.269	0.274	0.271	0.284	0.275
122	0.278	0.298	0.267	–	–	–	–	–	–	–
checkpoint	0.396	0.371	0.361	checkpoint	0.39	0.374	0.383	0.369	0.368	0.355
average value	0.2469	0.250	0.2484	average value	0.257	0.251	0.2483	0.2492	0.2479	0.2468

Fig. 5. Modifications of modeling the situation in 2015 at the "Base-S" industrial site for the research in the period from 2012 to 2019 (RRP measurement interval = 0 meters) and construction of 2-D model map with a grid size of 50 × 50 meters

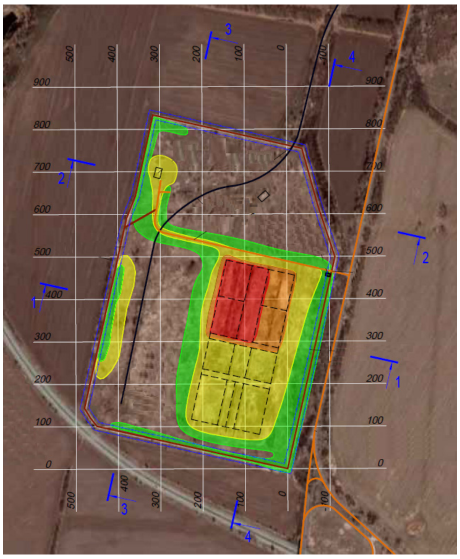

Fig. 6. Modifications of modeling the situation in 2015 at the "Base-S" industrial site for the research in the period from 2012 to 2019 (RRP measurement interval = 40 meters) and construction of 2-D model map with a grid size of 100 × 100 meters

At the *3rd* stage, a 3D model of the "Base-S" industrial site was built on the cardinal points, with the model transferred to a real map of the area (using the Google Maps 3D application). Fig. 7 shows the implementation of a 3D model of the industrial site "Base-S", combined with a graphic map; a 3D model for 2009 with a view of the RHO from the eastern side is presented by way of illustration.

At stage 4, a 3D model of the "Base-S" industrial site was built in the cardinal directions, with the model transferred to a real map of the area (using the 3D Google Maps application). Fig. 8 presents the implementation of a 3D model of the "Base-S" industrial site, combined with a graphic map. For example, a 3D model for 2015 is presented with a view of the RHO from the eastern side (one side was selected as a matter of convenience for understanding the changes over 6 years).

The conducted studies allow us to determine the isolines of the control values of gamma radiation EDR (0.260, 0.430, 1.0, 5.0, 12.0 mSv/h), outline the contours of each zone, and identify which areas need to be bypassed or the time spent in them reduced and require more attention. This allows us to reduce the impact on the health of personnel from radionuclides in radiation-contaminated waste and structures. This approach can also be applied to other plain nuclear power plants of the Ukrainian NFC. As the results of the research have shown, there is still a threat of additional technogenic increased exposure of nuclear power plant personnel.

Conclusions. The authors' analytical, statistical, and field research was conducted on the territory of the "Base-S" industrial site in the period 2009–2019 according to a number of radiation and sanitary and hygienic regulations, in accordance with regulatory and legal requirements. The ranges of RRP fluctuations

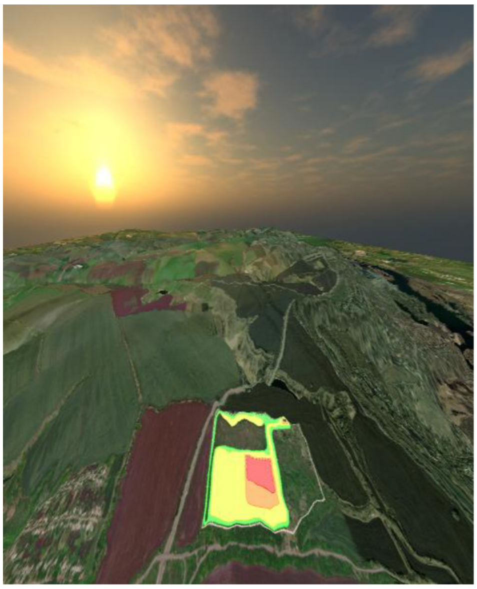

Fig. 7. View of the 3-D model of the industrial site "Base-S". View of the site from the east side (2009)

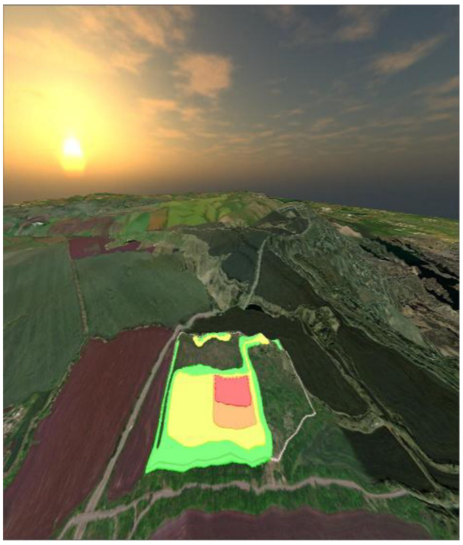

Fig. 8. View of the 3-D model of the industrial site "Base-S". View of the site from the east side (2015)

from maximum to minimum were determined for each section and the entire perimeter of the trail along which the personnel of SE "38 Viddil Inzhenerno-Tekhnichnykh Chastyn" and SE "Bar'yer" move around. Thereby, the dynamics of fluctuations in the values of the equivalent radiation dose power were determined, and additional studies were conducted regarding the required number of measurements to obtain the optimal time for people to stay on the perimeter.

Having a database of measurements for ADR, EDR, and FD, planar (2D) and volumetric (3D) models of presenting the obtained results were developed and implemented, with geolocation reference to each measurement point. Annual maps of radiation pollution for the EDR have been constructed; by analogy, maps of radiation pollution for other ADRs can be constructed by season, taking into account certain values of wind speed, temperature, and atmospheric stability category.

It has been established that the implementation of adaptation of the obtained measurement results through the presentation of data in the form of a 2D model and a 3D model is more informative and corresponds to the exact location of certain radiation zones, represented by four colors, which allows determining the place and time of being in a certain location, on a given segment, or in a certain zone of the "Base-S" industrial site. Moreover, zones with high concentrations of radionuclides, as time goes by, shift and change the contamination contour of each zone, which requires further monitoring studies and the application of a set of anti-radiation measures.

For the first time, a situation modeling was carried out, and a new methodological approach was developed for constructing 2D planar maps – a model of radiation contamination of the territory based on the determined RRPs of the "Base-S" industrial site.

In a scientific first, a situation modeling was carried out and a new methodological approach was developed for constructing 3D volumetric maps - a model of radiation contamination of the territory based on the determined radiation parameters (ADR/EDR) of the "Base-S" industrial site.

The conducted studies make it possible to outline the contours of each zone of values of the equivalent dose of radiation to personnel at their workplaces, identify which areas/locations should be given more attention, and determine where the time spent is critical for human health. This approach can also be applied to other plain radiation-hazardous facilities of the Ukrainian nuclear power plants.

Directions for future research. For the considered research methods in the conditions of the current RHO or for building 2D/3D models of radiation-contaminated territories, industrial sites with radiation sources, buildings, and structures, the most promising is modeling of processes using mathematical or analytical packages (GEANT, Ansys Fluent Transient Simulation) for building computer models using artificial intelligence. It is mandatory to strengthen the physical protection of the perimeters of the RHO through active and passive surveillance systems, with additional motion sensors along the perimeter of the territory of the "Base-S" industrial site. To reduce risks and occupational exposure of personnel, it is necessary to minimize the time security workers spend in the RHO. In the future, it is necessary to continue monitoring observations, as was decided for the "Sukhachivske" industrial site [23], with the construction of annual maps of radiation contamination [20]. In peacetime, it is necessary to use autonomous ground [24] and autonomous aerial remotely operated vehicles [25]. For future reference, the additional adjustments to research methods should be made based on the latest achievements set out in the ICRP recommendations.

Project number and name. This paper flows organically from the scientific developments of the Department of Labor Protection, Civil and Technogenic Safety of the Ukrainian State University of Science and Technology ERI "Prydniprovska State Academy of Civil Engineering and Architecture". Academic research work is carried out according to the cathedral subject "Employment protection, industrial, civil, and environmental safety in various spheres of human life" State Registration No. 0124U001896 (in the period 2024–2026).

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Дослідження радіаційної небезпеки на промисловому майданчику База-С із застосуванням моделювання

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Мета. Провести комплексні експериментальні дослідження на промисловому майданчику колишнього уранового виробництва виробничого об'єднання «Придніпровський хімічний завод» і визначити значення потужності еквівалентної дози гамма випромінювання для прогнозування динаміки змін радіаційного забруднення на промисловому майданчику База-С.

Методика. У роботі застосовані теоретичні, статистичні, аналітичні й графічні методи моделювання із застосуванням 2D/3D моделей на об'єктах ядерно-паливного комплексу, до яких відносяться радіаційно-небезпечні території, могильники, хвостосховища та промислові майданчики з радіоактивними речовинами, матеріалами чи відходами.

Результати. На основі проведених досліджень, визначені показники радіаційного забруднення за період 2009–2019 рр. Розроблені й реалізовані площинні (2D) та об'ємні (3D) моделі представлення отриманих результатів, із геолокаційною прив'язкою до кожної точки вимірювання. Побудовані щорічні карти радіаційного забруднення, що дозволяє проводити прогнозування ситуації в майбутньому.

Наукова новизна. Уперше, на основі отриманих даних, була проведена статистична й аналітична обробка результатів, з урахуванням специфіки розробленої плоскої чи об'ємної моделі, визначенням даних у вільних проміжках за рахунок апроксимації лінійної функції. Розроблені моделі реалізують принцип адаптації отриманих польових результатів вимірювання й дозволяють чіткіше визначати межі зон радіаційного забруднення промислового майданчику через представлення даних у вигляді 2D/3D візуалізації. Визначені показники радіаційної небезпеки на промисловому майданчику База-С і встановлені закономірності їх змін у часі, що дозволяє комплексно застосовувати протирадіаційні заходи. Уперше застосовані розроблені 2D/3D моделі, що відповідають точному розташуванню певних зон опромінення. Для більшого візуального сприйняття моделі запропоновано представляти різні зони чотирма кольорами (від зеленого до червоного). Це, у свою чергу, дозволяє визначати місце й час находження в певній локації, на даному відрізку або в певній зоні промислового майданчика База-С.

Практична значимість. На основі отриманих експериментальних результатів розроблені методичні рекомендації щодо втілення розробленої нової методики, що є вдосконаленням існуючих підходів до пішої й дистанційної гамма зйомки та впровадження процесів моделювання можливих ситуацій на радіаційно-забруднених об'єктах. Побудовані 2D/3D моделі дозволяють оцінити реальний стан речей на промисловому майданчику у часі й зменшити ризик додаткового опромінення персоналу радіаційно-небезпечного об'єкту, колишнього уранового виробництва ВО «ПХЗ», розташованого у Дніпропетровській області.

Ключові слова: *радіаційна небезпека, доза опромінення, периметр хвостосховища, 2D/3D модель, промисловий майданчик*

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