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Methodological principles of searching for disposal sites of radioactively contaminated materials by geophysical methods

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ABSTRACT

This article is devoted to radiometric studies at one of the sites of the Chornobyl nuclear power plant (the "Sandy Plateau" site), which is located on the south-eastern outskirts of the city of Pripyat. Radioactive substances, both artificial and natural, resulting from incidents and disasters at nuclear facilities pose the greatest danger. The disposal sites for radioactively contaminated materials considered in this work are sources of groundwater pollution. Currently, there is a problem of searching for their location for reburial in specialized stationary burial grounds, to solve which detailed complex geophysical studies are used. Various geophysical methods are considered, including micro-sensing and radiometric studies, to determine the location of burials. Particular attention is paid to the analysis and interpretation of geophysical data, as well as the economic and practical aspects of the application of these methods. As a result of the study, it was established: that when searching and studying burial sites of radioactively contaminated materials, the use of surface gamma photography makes it possible to assess the level of radioactive contamination of the upper layers of the soil (to a depth of 0.8-1 m). However, if the thickness of buried radioactively contaminated materials exceeds a certain level, which leads to weak contamination of rocks at a depth of more than 1-1.5 m, then burial objects may go undetected when using only gamma-ray imaging. In such cases, microgamma probing becomes an effective method. Increased values of exposure dose rate and the nature of microgamma sounding curves serve as indicators of the presence (increase in exposure dose rate with depth) or absence (sharp decrease in exposure dose rate with depth) of radioactively contaminated materials in the studied area.

Keywords: radioactive contamination, geophysics, research, complexing, micro gamma sounding, decontamination.

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Introduction

One of the greatest dangers is the radioactive pollution of the environment by man-made and natural radionuclides after accidents and catastrophes at nuclear cycle facilities. By-products of nuclear energy production pose long-term risks to human health and the environment [1]. The accident on April 26, 1986, at the Chornobyl nuclear power plant, which led to the release of large amounts of radionuclides into the environment, led to serious contamination of the surrounding area [[2], [3]].

As a result of the clean-up efforts of the accident in 1986-87, waste dumps containing approximately

106 m3 of low-level waste were created [4]. These waste dumps largely do not comply with regulatory requirements for low-level waste disposal sites and pose a radiation hazard to the environment.

According to an assessment by the Nuclear Energy Agency Committee on Radiation Protection and Public Health, "...all of these wastes are a potential source of groundwater contamination that will require careful monitoring until safe disposal in an appropriate repository can be achieved." and that "...large uncertainties remain which require correspondingly greater characterization efforts" [5].

In 1999-2003, an international team of French and Ukrainian institutes studied the behavior of radionuclides from the Chornobyl fallout at an experimental site in the area of the "Red Forest" landfill near the Chornobyl nuclear power plant. The Chornobyl Pilot Site (CPS), established as part of the project, became a field installation for in-situ confirmation and development of models of radionuclide migration in soils and the geosphere [[6], [7]].

In 1986-1988, temporary disposal sites of radioactively contaminated materials, decontamination waste, radioactively contaminated structures and equipment were carried out in the Chornobyl exclusion zone without proper engineering training for special burial grounds. Due to the emergency, the work was carried out urgently, while in almost most cases, proper topographic mapping of the disposal sites of radioactively contaminated materials was not ensured. In this regard, at this time, the location of many of them is unknown. Meanwhile, these disposal sites are sources of groundwater pollution that feed the Pripyat River and its tributaries. Nowadays, there is a problem of searching for them to reburial them in specialized stationary burial grounds.

The task of finding disposal sites for radioactively contaminated materials can be solved only through the use of detailed integrated geophysical studies. From the point of view of geophysics, the main types of pollution of the geological environment are radioactive and geochemical. As a result of studying the geological environment by geophysical methods, static and dynamic (time-varying) geophysical anomalies over pollution sources are detected [[8], [9]].

Tasks and complex of geophysical research

Geophysical methods are widely used in engineering-geological, geoecological and archaeological research. Analyzing the experience of using geophysical methods in solving engineering problems, it was determined that the tasks of searching for disposal sites of radioactively contaminated materials are practically similar to the tasks that are set before geophysical methods in the process of archaeological research.

The possibility of using geophysical research is based on a noticeable difference in the electromagnetic and radiometric parameters of both archaeological and man-made objects, compared with the surrounding host rocks. At the same time, the following basic tasks are solved using geophysical methods:

- mapping of trenches, mine workings, dams, ditches;
- search and exploration of disposal grounds, necropolises, underground structures, armament depots, and disposal sites of radioactively contaminated materials [[10], [11]].

A specific feature of the search for disposal sites of radioactively contaminated materials is the determination of radiometric parameters of radioactively contaminated materials and host soils. The experience of using geophysical methods for this purpose and the analysis of literary data indicates that the solution to the above tasks is a rather complex problem and requires the use of detailed integrated geophysical studies, as well as experimental and methodological work to improve the selected complex [[1], [2], [3], [4], [5], [12]].

From our point of view, a set of geophysical methods for searching and exploration of natural reserves should include:

- micro-electrical profiling using the electrical resistance method in various modifications, based on measuring the resistance of soils and rocks using electric currents;
- electrical profiling using the natural electric field method, which allows identifying zones with anomalous conductivity, which may indicate the presence of radioactive waste or changes in the composition of soils;
- microelectric sounding for detailing detected anomalous areas, allowing to localize of the sources of anomalies and determining their nature using point measurements of electrical resistance at shallow depths;
- the induced polarization method using the median gradient method is used to assess the polarizability of rocks and identify zones with

increased content of metals or organic substances, which may be associated with the disposal of radioactive waste;

• GPR sensing is effective for searching for containers with radioactive waste and mapping the structures of underground voids. The method uses radio waves to obtain images of underground structures, making it possible to detect various objects and anomalies at depths of up to several tens of meters with high resolution;

• micromagnetic studies involve measuring the Earth's magnetic field to identify local anomalies caused by the presence of magnetic materials or changes in the magnetic properties of rocks;

• surface and borehole gamma survey - measures the level of natural radioactivity of rocks and soils;

• as well as laboratory radiometric studies.

At the same time, the rational complex of specialised geophysical research in each specific case is determined by the tasks and economic factors.

Geophysical surveys are carried out in a profile-area version and should be sufficiently detailed, the observation step is several meters, and when anomalies are detailed – tens of centimeters. Parametric observations are performed on known objects and serve as exemplary models for interpreting the results of observations on ordinary profiles [[13], [14]].

Some positive experiences of such work have been accumulated. An example is the search for military equipment that sank in the swamps in 1941-1944 and the disposal sites of German soldiers on the fields of the Korsun-Shevchenko Battle. At the same time, detailed magnetometric surveys, as well as studies using natural electric field and microelectroprofiling methods (searching for craters from explosions of aerial bombs, artillery shells, remnants of iron structures, and weapons) turned out to be quite effective [[15], [16], [17]].

The processing of the received materials consists in their complex interpretation and analysis of the entire data set. As a result, anomalous zones are highlighted, which may be related:

- with a violation of the integrity of rocks (based on the materials of micro electroprofiling, microelectrosonding and GPR studies);

- with the presence of steel fragments (based on the materials of micromagnetic survey);

- with electrochemical processes (oxidation of metal fragments) occurring in the body of the disposal (based on the methods of natural electric field and induced polarization);

- with the presence of soils and materials intensively contaminated with radioactive substances – products of nuclear accidents and waste from radiochemical production (based on materials from surface and spur gamma-ray surveys).

Based on the results of the performed geophysical studies, a set of geophysical maps and sections is being built, which allow us to conclude that there is a disposal of radioactively contaminated materials in the studied area, as well as to determine the points of opening the body of disposal by wells and pits.

Experimental part

As an example of such work, we will present some materials of radiometric studies at one of the sites of the Chornobyl nuclear power plant (the Sandy Plateau site). The site is located on the southeastern outskirts of the city of Pripyat. Before the accident at the Chornobyl nuclear power plant, this area was washed with river sand 2 m thick and was planned for the construction of a new massif in Pripyat. Uncontaminated river sand is characterized by an exposure dose rate of 4-8 μR/h. Figure 1 shows a fragment of the 137Cs surface pollution map of the Chornobyl exclusion zone with the research area marked on it.

In 1988, experimental decontamination works were carried out at the research site by removing the top layer of soil with a thickness of 10 cm. In accordance with technical specifications, highly active soil should be buried on the same site, but information about the location of the disposal turned out to be lost. Many years later, the urgent task of searching for temporary disposal of radioactively contaminated soil removed during decontamination works arises. To solve this problem, areal studies were performed at the work site using the biolocation method over a network of 20×10 m. Based on the materials of these works, elongated anomalies were identified, the nature of which at the first stage was associated with the presence of trenches with radioactively contaminated soil. However, selective drilling of individual biolocation anomalies did not yield positive results [[18], [19], [20]].

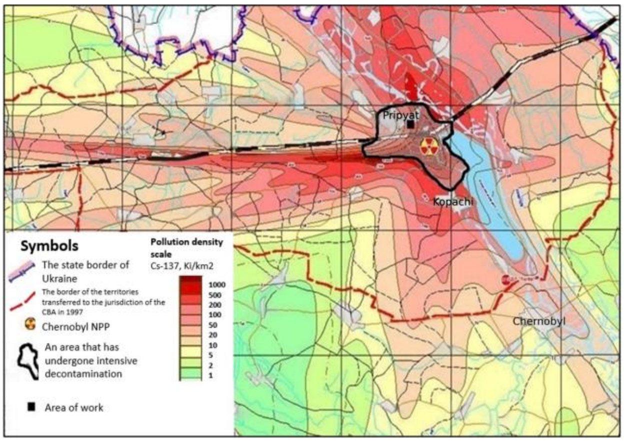

Figure 1 - Fragment of 137Cs surface contamination map: The scale 1:200 000

To check the detected anomalies, a surface gamma survey was performed over a 20×5 m network using a SRP-68-01 radiometer, the results of which are shown in Figure 2. At points where the exposure dose rate of γ-radiation (P) exceeded 3000 μR/h, measurements were repeated using the SRP-68-03 spur radiometer.

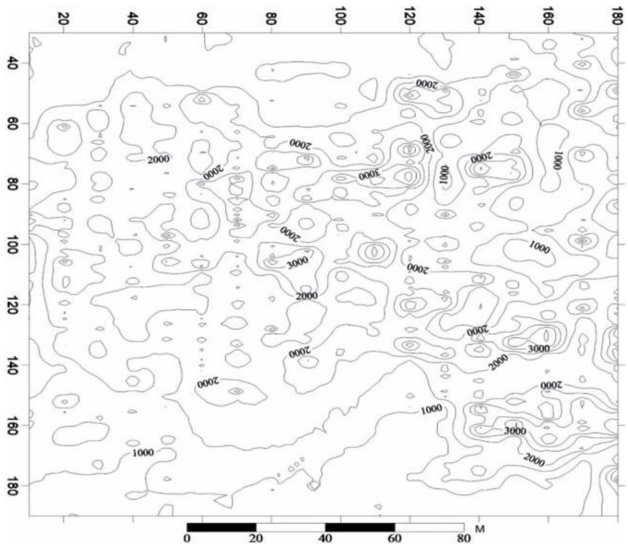

Figure 2 - Map of the exposure dose rate of γ-radiation (P). The «Sandy Plateau» site: The scale is 1:2 000. The isolines are drawn through 500 μR/h.

The exposure dose rate of γ-radiation at the research site varies from 350 μR/h to 4250 μR/h. The areas with increased exposure dose rates (2000 – 4000 μR/h) are localized in the central and southeastern parts of the research area, and the areas with reduced P values (350 – 1500 μR/h) are located in the northern, northeastern, southern and western parts of the site. The average values of the exposure dose rate of γ-radiation at the research site are 1800 μR/h. According to the materials of the «Kirovgeologiya» production association, the background values of the exposure dose rate of γ-radiation of territories composed of river sands in the research area ranged from 4 μR/h to 8 μR/h.

The gamma field has a mosaic, sometimes backstage nature, which may be the result of uneven removal of the upper highly active layer by earthmoving machines during decontamination. At the same time, the negative forms of the microrelief were partially «sprinkled» with highly active soil, and the positive ones, on the contrary, were cut to a great depth.

To assess the degree of radioactive contamination, the specific activity of ^{137}Cs was calculated using the well-known formula:

$$A_{Cs} = \frac{P \cdot \mu_{эф}}{2 \cdot \pi \cdot K_{\gamma Cs} \cdot \rho},$$

where *P* – exposure dose rate, μR/h; $\mu_{эф}$ – effective attenuation coefficient of γ-radiation; $K_{\gamma Cs}$ – gamma equivalent of ^{137}Cs; ρ – density of rocks, g/cm³. A fragment of the pollution assessment map of the ^{137}Cs site is shown in Figure 3.

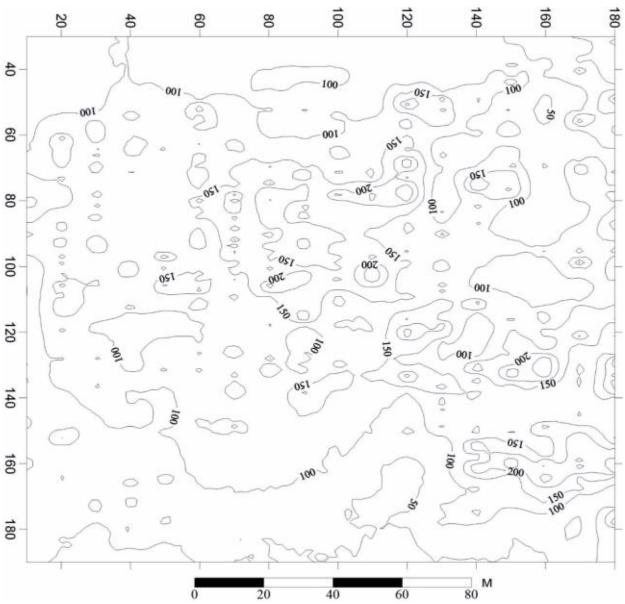

Figure 3 - Map of the specific activity of 137Cs (ACs) of the topsoil. The «Sandy Plateau» site: The scale is 1:2000. The isolines are drawn through 500 kBq/kg.

For the study area, the specific soil activity caused by ^{137}Cs in the depth range of 0-50 cm varies from 24 kBq/kg to 291 kBq/kg with an average value of 121 kBq/kg.

For operational analysis of gamma survey materials, graphs of exposure dose rate and specific activity of 137Cs were constructed along profiles that stretched from south to north. The exposure dose rate is related to the level of radiation exposure and is taken into account when planning radiation protection measures and environmental monitoring. The specific activity of cesium shows how much a specific mass of material is contaminated with the radionuclide. High specific activity may indicate significant radioactive contamination requiring decontamination measures or access restrictions. These indicators are used to assess current conditions, plan protection measures and respond to radiation accidents.

Figure 4 shows the materials of the surface gamma-ray survey according to profile 8 (graph of exposure dose rate and specific activity of ^{137}Cs), typical for the research area.

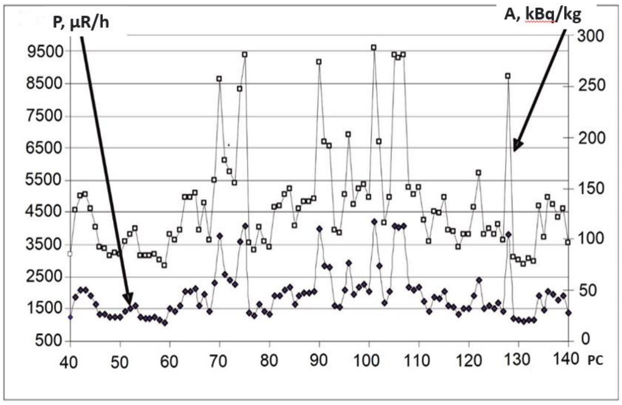

Figure 4 - Graphs of the exposure dose rate (P) and specific activity of 137Cs of the topsoil (A) according to profile 8

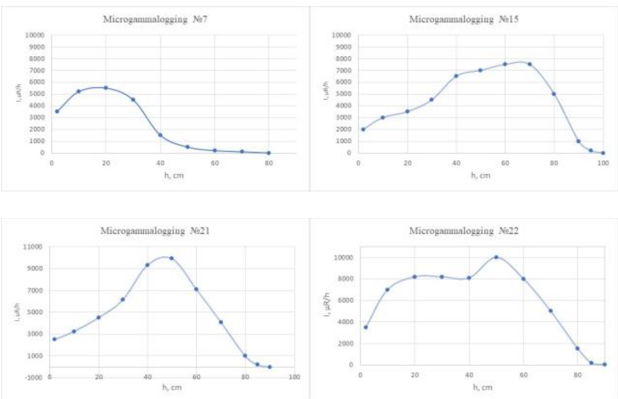

Figure 5 - Graphs of the dependence of the change in the exposure dose rate (I) on the depth (h), characteristic of microgammasondings performed at the «Sandy Plateau» site.

A comprehensive analysis of the γ-radiation exposure dose rate map and the biolocation research scheme revealed that the correlation of biolocation and surface γ-anomalies is often absent [20].

To check the anomalous zones identified by biolocation and surface γ-survey, microgammasonding was performed, the characteristic types of which are shown in Figure 5.

Results and Discussion

The materials of the microgammasonding curves show that the value of the exposure dose rate at depths of 2-10 cm ranges from 1300 μR/h to 7000 μR/h and tends to increase with depth. With a further increase in the measurement depth (up to 50 – 70 cm), different behaviors of the exposure dose rate graph are observed, depending on the depth of penetration of technogenic radionuclides into the soil: the values remain at the same level, increase or in some cases decrease. The final branch of all microgammasondings has a descending nature, and the exposure dose rate decreases to tens of μR/h, i.e. almost to the background. Analysis of microgammasonding data shows that the penetration depth of technogenic radionuclides is up to 50-60 cm. The nature of the behavior of microgammasonding curves (a sharp decrease in the exposure dose rate after 30-60 cm with a depth) allows us to conclude that there is no disposal of radioactively contaminated soil in the surveyed area.

Conclusions

The complex of geophysical methods in the search and exploration of disposal sites of radioactively contaminated materials includes surface and spur gamma-ray surveys, microelectroprofiling by the process of electrical resistance in various modifications, electroprofiling by the method of natural electric field, microelectrosonding when detailing detected anomalous areas, the method of induced polarization by the method of median gradient, micromagnetic and geolocation studies, as well as laboratory radiometric studies. The tasks and economic factors determine a rational complex of specialised geophysical research in each specific case, while geophysical surveys should be sufficiently detailed.

During the search and exploration of disposal sites for radioactively contaminated materials, surface gamma-ray surveys allow us to assess the radioactive contamination of the topsoil (up to a depth of 0,8-1 m), but with the capacity of overlapping disposal sites for radioactively contaminated materials of slightly contaminated rocks of more than 1-1,5 m, the search object may not be fixed.

Microgammasonding is an effective method for determining the disposal of radioactively contaminated materials. High values of exposure dose rate and the behavior of microgammasonding curves are criteria for the presence (increase in exposure dose rate with depth) or absence (sharp decrease in exposure dose rate with depth) of disposal of radioactively contaminated materials at the surveyed site.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Радиоактивті ластанған материалдар көмілген жерлерді геофизикалық әдістермен іздеудің әдістемелік принциптері

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ТҮЙІНДЕМЕ

Бұл мақала Припять қаласының оңтүстік-шығыс шетінде орналасқан Чернобыль атом электр станциясы учаскелерінің біріндегі («Құмды үстірт» учаскесі) радиометриялық зерттеулерге арналған. Ядролық қондырғылардағы апаттардың әсерінен пайда болған жасанды және табиғи радиоактивті заттар үлкен қауіп төндіреді. Радиоактивті ластанған материалдар көмілген орындар жер асты суларын ластайды Қазіргі уақытта мамандандырылған стационарлық қорымдарда қайта көму мақсатында олардың орналасқан жерін іздеу мәселесі тұр, оны шешу үшін егжей-тегжейлі кешенді геофизикалық зерттеулер қолданылады. Жерлеу орындарының орнын анықтау үшін әртүрлі геофизикалық әдістер қарастырылады, соның ішінде микро-сенсорлық және радиометриялық зерттеулер. Геофизикалық мәліметтерді талдау мен түсіндіруге, сондай-ақ осы әдістерді қолданудың экономикалық және практикалық аспектілеріне ерекше назар аударылады. Зерттеу нәтижесінде анықталғаны: радиоактивті ластанған материалдар көмілген жерлерді іздестіру және зерттеу кезінде жер үсті гамма-фотосуретін пайдалану топырақтың жоғарғы қабаттарының (тереңдікке дейін) радиоактивті ластану деңгейін бағалауға мүмкіндік береді. 0,8-1 м). Алайда, егер көмілген радиоактивті ластанған материалдардың қалыңдығы белгілі бір деңгейден асып кетсе, бұл 1-1,5 м-ден астам тереңдіктегі тау жыныстарының әлсіз ластануына әкеліп соқтырса, онда көму объектілері тек гамма-сәулелік бейнелеуді қолданғанда анықталмай қалуы мүмкін. Мұндай жағдайларда микрогамма зондтау тиімді әдіске айналады. Экспозиция дозасының жылдамдығының жоғарылауы және микрогамма зондтау қисықтарының сипаты зерттелетін аумақта радиоактивті ластанған материалдардың болуы (тереңдікпен экспозициялық доза жылдамдығының жоғарылауы) немесе жоқтығы (тереңдікпен экспозициялық доза жылдамдығының күрт төмендеуі) көрсеткіштері ретінде қызмет етеді.

Түйін сөздер: радиоактивті ластану, геофизика, зерттеу, комплекстеу, микрогаммалық зондтау, залалсыздандыру.

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Методические принципы поисков пунктов захоронения радиоактивно загрязненных материалов геофизическими методами

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АННОТАЦИЯ

Данная статья посвящена радиометрическим исследованиям на одном из участков Чернобыльской АЭС (участок «Песчаное плато»), который расположен на южно-восточной окраине г. Припять. Радиоактивные вещества, как искусственного, так и естественного происхождения, возникшие из-за инцидентов и катастроф на ядерных объектах, представляют наибольшую опасность. Рассматриваемые в данной работе пункты захоронения радиоактивно загрязненных материалов являются источниками загрязнения подземных вод. В настоящее время существует проблема поисков их местоположения с целью перезахоронения в специализированные стационарные могильники, для решения которой используются детальные комплексные геофизические исследования. Рассматриваются различные геофизические методы, включая микрогаммазондирование и радиометрические исследования, для определения местоположения захоронений. Особое внимание уделяется анализу и интерпретации геофизических данных, а также экономическим и практическим аспектам применения этих методов. В результате исследования установлено: при осуществлении поиска и исследовании мест захоронения радиоактивно загрязненных материалов использование поверхностной гамма-съемки позволяет оценить уровень радиоактивного загрязнения верхних слоев грунта (до глубины 0,8-1 м). Однако, если мощность захороненных радиоактивно загрязненных материалов превышает определенный уровень, что приводит к слабому загрязнению пород на глубине более 1-1,5 м, то объекты захоронения могут остаться незамеченными при использовании только гамма-съемки. В таких случаях эффективным методом становится микрогаммазондирование. Повышенные значения мощности экспозиционной дозы и характер кривых микрогаммазондирования служат индикаторами наличия (увеличение мощности экспозиционной дозы с глубиной) или отсутствия (резкое снижение мощности экспозиционной дозы с глубиной) радиоактивно загрязненных материалов в изученном участке.

Ключевые слова: радиоактивное загрязнение, геофизика, исследования, комплексирование, микрогаммазондирование, дезактивация.

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References

[1] Ewing RC, Weber WJ, Clinard FW. Radiation effects in nuclear waste forms for high-level radioactive waste, Progress in Nuclear Energy. 1995; 29(2):63-127.

[2] Gudkov D, Kuzmenko M I, Kireev S I, Nazarov A B, Shevtsova N L, Dzyubenko E V, Kaglyan A. Radioecological problems of aquatic ecosystems of the Chernobyl exclusion zone, Biophysics. 2009; 55:332-339.

[3] Oughton DH, and Kashparov V, (eds.). Radioactive Particles in the Environment. Van Meir N, Bugai D, Kashparov V. The experimental platform in Chernobyl: an international research polygon in the exclusion zone for soil and groundwater contamination. 2009, 197-208. https://doi.org/10.1007/978-90-481-2949-2_13

[4] Dzhepo SP, Skalskij AS, Bugai DA, Marchuk VV, & Waters RD. Geologicheski Zhurnal. 1994; 4(6):100-108. (in Russ.).

[5] Nuclear Energy Agency (NEA), Chernobyl–Ten years on radiological and health impact. An appraisalby the NEA Committee on radiation protection and public health. Reprint. Paris: OECD. 1996.

[6] Dewière L, Bugai D, Kashparov V, and Barthès V. Validation of the global model for 90Sr migration from the waste burial in the Chernobyl exclusion zone. Radioprotection. 2005; 40(1). https://doi.org/10.1051/radiopro:2005s1-038

[7] Bugai D, Skalskyy A, Dzhepo S, Kubko Yu, Kashparov V, Van Meir N, Stammose D, Simonucci C, Martin-Garin A. Radionuclide migration at experimental polygon at Red Forest waste site in Chernobyl zone. Part 2: Hydrogeological characterization and groundwater transport modeling, Applied Geochemistry. 2012; 27(7):1359-1374.

[8] Vyzhva SA, Onyshchuk VI, Onyshchuk II, Reva MV. Inzhenerna heofizyka. Kyiv. VPTs Kyivskyi universytet. 2018, 591. (in Ukrainian).

[9] Vizhva SA, Onishchuk II, CHernyaiev OP. YAderna geofizika. Kiiv. VPC Kiivskij universitet. 2012, 608. (in Ukrainian).

[10] Evangeliou N, Hamburger Th, Talerko N, Zibtsev S, Bondar Yu, Stohl A, Balkanski Y, Mousseau T, Moller A. Reconstructing the Chernobyl Nuclear Power Plant (CNPP) accident 30 years after. A unique database of air concentration and deposition measurements over Europe, Environmental Pollution. 2016; 216:408-418. https://doi.org/10.1016/j.envpol.2016.05.030

[11] Briechle S, Molitor N, Krzystek P, Vosselman G. Detection of radioactive waste sites in the Chornobyl exclusion zone using UAV-based lidar data and multispectral imagery, ISPRS Journal of Photogrammetry and Remote Sensing. 2020; 167:345-362. https://doi.org/10.1016/j.isprsjprs.2020.06.015

[12] Aliev S, Omarbekov Y. Influence of the "pumping wells" technology on the indicators of in situ leaching of uranium. Complex Use of Mineral Resources. 2021; 2(317):30-36. https://doi.org/10.31643/2021/6445.15

[13] Wang J, Chen L, Su R, Zhao X. The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: planning, site selection, site characterization and in situ tests, J. Rock Mech. Geotech. Eng. 2018; 10(3):411-435.

[14] Davids C, Tyler AN. Detecting contamination-induced tree stress within the Chornobyl exclusion zone, Remote Sensing of Environment. 2003; 85(1):30-38.

[15] Ya-ci Liu, Yu-hong Fei, Ya-song Li, Xi-lin Bao, Peng-wei Zhang. Pollution source identification methods and remediation technologies of groundwater: A review, China Geology. 2024; 7(1):125-137.

[16] Arkhipov NP, Kuchma ND, Askbrant S, Pasternak PS, Music VV. Acute and long-term effects of irradiation on pine (Pinus silvestris) stands post-Chernobyl, Science of The Total Environment. 1994; 157:383-386.

[17] Vyzhva SA, Onyshchuk VI, Onyshchuk II, Reva M, Shabatura O. Identification of burial sites of radioactive contaminated materials using geophysical methods. 17th International Conference on Geoinformatics - Theoretical and Applied Aspects. 2018; 2018:1-6. https://doi.org/10.3997/2214-4609.201801825

[18] Agnew K, Cundy AB, Hopkinson L, Croudace IW, Warwick PhE, Purdie Ph. Electrokinetic remediation of plutonium-contaminated nuclear site wastes: Results from a pilot-scale on-site trial. Journal of Hazardous Materials. 2011; 186(2-3):1405-1414. https://doi.org/10.1016/j.jhazmat.2010.12.016

[19] Bonzom J, Hättenschwiler S, Lecomte-Pradines C, Chauvet E, Gaschak S, Beaugelin-Seiller K, Della-Vedova C, Dubourg N, Maksimenko A, Garnier-Laplace J, Adam-Guillermin Ch. Effects of radionuclide contamination on leaf litter decomposition in the Chernobyl exclusion zone, Science of The Total Environment. 2016; 562:596-603. https://doi.org/10.1016/j.scitotenv.2016.04.006

[20] Kashparov V, Salbu B, Levchuk S, Protsak V, Maloshtan I, Simonucci C, Courbet Ch, Lien Nguyen H, Sanzharova N, Zabrotsky V. Environmental behaviour of radioactive particles from Chornobyl, Journal of Environmental Radioactivity. 2019; 208–209. https://doi.org/10.1016/j.jenvrad.2019.106025