SECTION 2
THERMAL AND FAST REACTOR MATERIALS

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SIMULATION OF RADIONUCLIDE PROPAGATION AT EXTERNAL EXTREME EVENTS IN THE NPP AREA

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At the current stage of electric-power industry development in Ukraine, the issues of energy safety and energy independence are becoming increasingly important. Being the largest among others in Europe, Zaporizhzhia Nuclear Power Plant (ZNPP) has a large dry storage facility for spent nuclear fuel. The armed attack of Russia has endangered nuclear and physical safety in Ukraine. Beginning on 24 February, 2022, the hostilities were activated in the country. The activization of the warfare has led to the capture of the ZNPP by the Russian militaries (4 March, 2022) and to their presence of the ZNPP. This situation causes justifiable concern about the potential detrimental effect on the nuclear and physical safety under service conditions of nuclear power units and at radioactive source-related activities. This paper is concerned with simulation of the radionuclide propagation under external extreme events in the NPP zone, using the ZNPP as an example. The transfer of ^{137}Cs radionuclide has been simulated for the hypothetical ZNPP failure at meteorological conditions as of 23 to 25 August, 2022. According to the simulation data, throughout 23–25 August, 2022, the highest ^{137}Cs concentration values might be observed within the Ukraine territory, particularly in the near-field zone, 50…100 km in radius, from the emission point. Besides, the radioactive impurities could be carried off to the neighboring state areas.

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INTRODUCTON

Atomic energetic holds one of the leading positions in the national economy of Ukraine and supports nuclear-power engineering as an important line of the national safety. After decommissioning of the Chernobyl NPP in Ukraine, there still remain in operation four nuclear-power stations with WWER-type reactors. These are the Zaporizhzhia, South Ukraine, Rivne and Khmelnytskyi NPPs, having in service 15 nuclear power units with the overall installed nuclear capacity of 13835 MW. The Ukrainian NPS make use of the reactor installations, most of which being the Type WWER-1000/320, totaling to 11 units. Two of them were put in commercial operation at Khmelnytskyi and Rivne NPPs in 2005 and 2006, respectively. Since 1996, the management of the Zaporizhzhia, South Ukraine, Rivne and Khmelnytskyi NPPs has been the responsibility of the State Enterprise "National Atomic Energy Generating Company" [1].

In wide-ranging application of nuclear technologies, the humanity has faced the problems that involve extraordinary responsibility for the solutions and activities in the field of atomic power engineering. The use of nuclear technologies has brought about a new type of global danger, in which many generations of people would be bound to live even if they would have to abandon fully the nuclear energetic (spent nuclear fuel (SNF) issues).

At the current stage of electric-power industry development in Ukraine, the issues of energy safety and energy independence are becoming increasingly important. In this regard, the leading role in the management of SNF in Ukraine belongs to the ZNPP. Being the largest among others in Europe, the ZNPP has the great at-reactor dry storage facility for spent nuclear fuel. The creation and putting into operation of the ZNPP dry storage facility for SNF as a constituent of the Ukrainian energy-independence, as well as its further safe functioning are impossible without scientific-technical maintenance that involves the development and updating of techniques for determining nuclear and radiation safety parameters, and also the development of a package of measures in compliance with the safe thermal conditions for the storage [2].

The armed conflict endangers nuclear and physical safety in Ukraine. Beginning on February 24, 2022, the hostilities were activated in the country. The activization of the warfare has led to the capture of the ZNPP by the Russian militaries and their presence on of the plant (4 March, 2022). This situation causes justifiable concern about the potential detrimental effect on the nuclear and physical safety under service conditions of nuclear power units and at radioactive source-related activities.

The present paper is concerned with simulation of the potential radio-contamination of Ukraine and neighboring countries in case of ZNPP incidents resulting from unprovoked hostilities of Russia against Ukraine.

1. SUBJECT OF STUDY AND INPUT DATA

The ZNPP is situated on the Kakhovka reservoir shoreline at a distance of 400 km southeastward from Kyiv, in the steppe zone of Ukraine. Nearby, there is the satellite town Ehnergodar. The first four power generating units were put into operation in the years from 1984 to 1987. The fifth and the sixth power units were commissioned for service in 1989 and 1995, respectively. The reactor type was chosen to be WWER-1000 (pressurized water). The gross station output is 6000 MW. The plant generates 40 to 42 milliards kW/h, this being the fifth part of the average annual energy generation in Ukraine and about 47% of electrical energy generated by all Ukrainian NPPs. The ZNPP is connected to the Unified Energy System of Ukraine by means of three 750 kV power transmission lines and one 330 kV power line.

The territorial structure of the Left-shore part of the region is noteworthy for the Ehnergodar industrial center. The power outputs of the Zaporizhzhia hydroelectric power plant and nuclear power plant form its basis (Fig. 1) [1].

Fig. 1. The ZNPP layout map

North-east winds predominate here. The air quality is adversely affected by activities of neighboring pollutive production enterprises (combined heat and power stations, mining companies, metallurgical engineering). Long-term data are indicative of the absence of NPP radiation effect on the air quality in the ZNPP area. For cooling purposes, the ZNPP makes use of the water from the cooling pond connected via the artificial channel with the Kakhovka water-storage reservoir.

The main contributors to the formation of dose loads on the people living within the 30-km area of the ZNPP are: the natural radioactive nuclides, including those comprised in the emissions of Zaporizhzhia hydroelectric power plant; the artificial radio nuclides ^{90}Sr and ^{137}Cs from global pollutions; ^{90}Sr and ^{137}Cs fallouts of the Chernobyl NPP accident emission; and also, a wide range of radionuclides comprised in emissions and releases of the ZNPP.

In air emissions the main portion of activity falls on the for inert radioactive gases such as ^{133}Xe, ^{135}Xe, ^{41}Ar; in aerosols, the short-lived ^{88}Ru and ^{138}Cs isotopes (half-life periods of < 24 h) are predominant. The long-lived isotopes (half-life periods of > 24 h) are mainly represented by ^{60}Co, ^{54}Mn, ^{24}Na, ^{51}Cr, etc. Iodine radioisotopes are present in emissions in both the aerosol and gaseous forms. The amount of ^{137}Cs and ^{89,90}Sr radioisotopes in emissions is negligible. Yet, in view of their high biological significance, the occurrence of these radioisotopes is always under permanent monitoring [3, 4].

Table lists the estimated values of average annual radionuclide concentrations in the uppermost layer of soil and the estimated annual doses of radiation from gas-aerosol ZNPP emissions at the sanitary protection zone boundary. The maximum overall individual dosage can range up to 0.044 mZv/year, this being no more than 0.11% of the doses limit (40 mZv/year). The major contribution to the radiation dose comes from inert radioactive gases.

Annual individual radiation doses at the ZNPP sanitary protection zone boundary, (2008) [1]

Radionuclides	Emissions, Bq/year	Average annual concentration in ground plots area, Bq/m^3	Cloud dose, Sv/year	Dose from soils, Sv/year	Inhalation dose, Sv/year	Peroral dose, Sv/year	Total dose, Sv/year	Share of radionuclides in the total dose, %
^{88}Kr	3.90E+12	9.6E-03	3.0E-08	0.0E+00	0.0E+00	0.0E+00	3.0E-08	68.0
^{133}Xe	2.81E+13	7.7E-02	3.2E-09	0.0E+00	0.0E+00	0.0E+00	3.2E-09	7.3
^{135}Xe	7.02E+12	1.9E-02	6.5E-09	0.0E+00	0.0E+00	0.0E+00	6.5E-09	14.7
^{131}I	9.04E+7	2.5E-07	1.3E-13	5.5E-11	7.4E-11	3.2E-11	1.6E-10	0.4
^{51}Cr	2.25E+07	6.1E-08	2.7E-15	1.6E-12	7.9E-14	2.5E-14	1.7E-12	0.004
^{54}Mn	2.46E+06	6.7E-09	8.0E-15	4.2E-11	3.7E-13	4.5E-12	4.7E-11	0.11
^{58}Co	2.90E+06	7.8E-09	1.1E-14	5.8E-11	5.7E-13	3.5E-12	6.2T-11	0.14
^{60}Co	7.47E+06	2.0E-08	7.8E-14	4.0E-10	2.2E-11	1.7E-10	5.9E-10	1.3
^{134}Cs	5.11E+06	1.4E-08	3.1E-14	1.6E-10	1.0E-11	1.1E-09	1.3E-09	2.9
^{137}Cs	1.05E+07	2.9E-08	2.4E-14	1.3E-10	3.7E-11	2.0E-09	2.2E-09	5.0
Total radiation dose, Sv/year			4.0E-08	8.5E-10	1.4E-10	3.3E-09	4.41E-08	100
Share in radiation, %			90.7	1.9	0.3	7.5	100	–

Currently the problem of SNF storage has become of vital importance on a global scale and, particularly, in Ukraine. Since the atomic energy proportion in the total electric energy output in Ukraine is traditionally high, making more than 50%, it is evident that the nuclear power reactors of four active NPPS annually produce a considerable amount of high-level radwastes, among them being the SNF [5–7].

The SNF resulting from energy generation in nuclear reactors is one of the most important NPP production run components. After service in the reactor core, nuclear fuel is unloaded into cooling pools, where it is kept for 4 to 5 years to reduce the residual energy liberation. After cooling in the pools, the SNF is loaded in special containers that ensure safety during transportation, and is directed to the spent-fuel storage.

The problem of handling the energy reactor SNF in our country is regulated in particular by the Order of the Ukrainian Ministry of Energy and Coalmining (No 386 as of 19.06.2015) "On adoption of Strategic lines of handling the SNF from Ukrainian atomic power plants with WWER-type reactors for the period up to the year of 2030 and Action Area Plans of their realization". The Order allows for a long-term storage of ZNPP SNF at the NPP storage facility [8, 9].

The dry storage facility for SNF at the ZNPP was put into operation in 2001 with its expected service life up to 50 years. The dry storage facility for SNF project has been realized on the basis of the American company technology (Duke Engineering and Services), meeting all the requirements of the guidelines, rules and standards of nuclear and radiation safety [10].

The mentioned technology involves the use of dry in vertical position. The dry storage method appears practical, since at the SFA storage in the cooling pools for no less than 5 years the residual energy liberation and radioactivity essentially decrease.

This fuel can be safely stored at the NPP site by the dry technique using the VSC, providing both effective heat removal from the SFA and sufficient biological protection against radiation impact on the NPP personnel, resident population, and the environment.

The SNF storage site is assumed to take up 380 containers, where 9000 cassettes can be stored. In 2022, 174 concrete containers were stored in the dry storage facility for spent nuclear fuel, each of them accommodating 24 spent fuel assemblies. All the components used in the container production are manufactured at the plants situated in the immediate vicinity of the ZNPP.

The average annual amount of SNF, which is discharged from a single WWER-type reactor for the storage, makes 42 fuel assemblies. At the ZNPP, about 252 fuel assemblies are annually in use.

Under standard operating conditions, the ZNPP exerts no negative radiation effect on the soils. However, in the event of an emergency, and depending on the nature of the emergency, a great deal of radioactive contaminants ejected into the atmosphere may fall out onto the earth surface.

One of the main functions in SNF transit and storage is to ensure radiation shielding. For a more than a three-year storage time, the highest γ-activity of SNF is contributed by four nuclides that undergo β-decay followed by gamma-ray emission from the daughter nuclides $^{90}Sr \rightarrow {}^{90}Y$, $^{106}Ru \rightarrow {}^{106}Rh$, $^{137}Cs \rightarrow {}^{137}Ba$, $^{144}Ce \rightarrow {}^{144}Pr$, and also, by ^{134}Cs and ^{154}Eu [11, 12].

The operating safety of any SNF storage is a complex concept, and aside from the nuclear and radiation safety measures, it includes the provision of appropriate environmental safety for thermal conditions during the whole service life of the storage facility, i.e., it calls for meeting the thermal safety requirements.

Generally, the results of investigations demonstrate the equipment reliability and the absence of any mechanical damages of the stored SNF. However, the question of how much the thermal conditions of storage would change in case of an accident remains open. A similar situation is developed for the only-in-Ukraine dry spent fuel storage facility at the ZNPP. Its safety analysis report comprises no data on the level of possible SNF temperatures under the conditions of some design accidents. The ZNPP spent fuel is stored in the outdoor container-type storage facility (Fig. 2). The spent fuel (24 SFA assemblies of the WWER-1000 reactor) is arranged in the metal leak-tight storage basket, which is placed, in its turn, in a concrete container [13].

Fig. 2. Dry container-type spent-fuel storage facility at the ZNPP

The numerical simulation data were used to estimate the maximum temperatures in the spent fuel storage container at some design accidents (container falling, storage basket displacement, weather factors). The container falling has been determined to be most dangerous from the thermal standpoint, as the level of maximum temperatures may exceed the permissible value 350 °C.

By the night on 4 March, 2022, Russian troops captured the ZNPP site. This has brought the direct threat to life of the plant personnel; bombardments and fires have resulted in damaging the equipment, building structures, pipe lines as well as the high-voltage power lines.

By the fact of forced capture of the ZNPP site and the following presence of RosAtom and RosTekhnadzor administrative agents in it, the Russian Federation has neglected the basic standards of nuclear safety and protectability. It has converted the object of peaceful nuclear energy use into the military base by locating the means of transportation and military enginery on the ZNPP premises and in the vicinity of power generating units. That has considerably aggravated the fire safety conditions and the timely access to the equipment in case of emergency situations.

As criteria of estimating the current state of safety at war conditions, Director-General of the IAEA has put forward seven indispensable fundamentals of nuclear safety, which follow from the IAEA principles and standards of safety. Meanwhile, all the seven indispensable fundamentals of nuclear safety were violated by bombardments, forced capture and occupation of the ZNPP site.

Nevertheless, the IAEA authorities still apply the mentioned fundamentals as indicators of the current state of the ZNPP safety. The integrity damage of the systems and elements, degradation of equipment without timely repairs and due technical maintenance service, an appreciable decrease in the number of the qualified in-plant personnel, weariness of people as a result of physical and psychological pressure, the damage of infrastructure for emergency preparedness and response within the ZNPP area and beyond, the loss of reliable connection with the regulatory authority, and also, the presence in the ZNPP area of outsiders and the Russian personnel having no experience of operating at updated power generating units of the ZNPP, all these factors bring the threat to the safe operation of the nuclear power plant.

The unprovoked and unjustifiable aggressive war of Russia against Ukraine has revealed a number of trouble spots from the standpoint of nuclear safety and protectability. Currently, the Russian war against Ukraine is assumed to carry risk of using nuclear weapons along with the threat of using peaceful atom for military purposes. Russia fired at Chernobyl NPP and ZNPP, subjected South Ukraine NPP and the Kharkov Institute of Physics and Technology to rocket attacks, made rocket attacks at other NPPs in Ukraine [14].

Continual hostilities at the ZNPP and its environs have affected the physical integrity of the installations, no matter whether those were the reactors, fuel cooling pools, or the radioactive waste storage facilities. On several occasions the rocket attacks resulted in damaging the constructions on the NPP site, in particular, the areas adjacent to the cooling pools and the dry spent fuel storage facility, and also damaged the power transmission lines on the site. The situation at the ZNPP remains to be insecure, unstable and complicated. At that, violations of the seven indispensable NPP site safety components are being registered over and over again.

Even though the stability of six reactor blocks, and the integrity of the spent fuel, fresh fuel and radioactive low-, mean-, and high-level waste forms located in the corresponding storage facilities on the site, are currently confirmed, the unceasing hostilities still present a severe hazard to physical integrity of the ZNPP [15].

During the period under report, the ZNPP power generating units No 1, 2, and 3 remained at cold shutdown conditions. During the greater part of the report period, power unit No 5 remained at hot shutdown conditions, however the ZNPP administration decided to switch the energy unit No 4 to the hot shutdown conditions, so that the energy unit No 5 could be transferred to the cold shutdown conditions for performing maintenance service. The transition was completed on July 28, 2023. The energy unit No 4 stayed in the hot shutdown conditions only up to 12 August, following which the ZNPP operators retransferred unit No 4 to the cold shutdown conditions after detecting water leakage from one of the four steam generators located inside the containment shell. For a greater part of the report period the energy unit No 6 stayed in the cold shutdown conditions, however on 13 August, 2023 it was transferred to the hot shutdown conditions to continue the process of steam production required on the site. The decision of the ZNPP administration relative to these transfers was in contradiction to the prescription of the State Inspectorate of nuclear regulation in Ukraine as of 8 June, 2023, about concerning the limitation on the license for the operation of energy unit No 5 (just as of all other energy generating units) by using cold shutdown conditions.

During the period under review, there was noted no effect on the physical integrity of six reactor power units, or the storage facilities on the site, where the spent fuel, fresh fuel and radioactive low-, mean- and high-level wastes are stored.

The dam destruction of the Kakhovk a water power station on 6 June, 2023, has resulted in a significant fall of water level in the water reservoir, which had been used by the ZNPP for the cooling-water intake necessary to maintain NPP safe operation. In turn, that called for seeking and finding alternative water supply sources.

During the period under report, disconnections from the base line of the external electric power supply were observed more than once. Although there was no total loss of external energy supply, there are strong grounds to suppose that the unstable situation still persists in the field of nuclear and physical safety on the NPP site [16].

2. ANALYSIS METHODS

For estimating the dynamics of contaminating radioactivity carry-over to the atmosphere at external extreme events in the ZNPP area, the following software products were used: NASA Worldview [17]; the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) program [18], developed in the NOAA Air Mass Laboratory (USA) and in the Australia Meteorology Bureau.

For identification of fires and estimation of their parameters, and relying on the NASA Worldview as a base tool, we have used the MODIS Fire and Thermal Anomalies product, which deals with the data from the satellites Terra (MOD14) and Aqua (MYD14), as well as the combined satellite product of Terra и Aqua (MCD14).

With the use of the meteorological data, the HYSPLIT program enables one to reconstruct the trajectories of radionuclide propagation in the atmosphere and to obtain the real pattern of radionuclide distribution within the area under investigation.

3. RESULTS OF THE RESEARCH

The ZNPP has not been designed to operate in the zone of warfare, therefore the shooting war close to the station presents a number of severe vicinity risks. One of the main anxieties expressed by experts relates to the risk of missile strikes at the nuclear waste storage. The breakdown of the containers is comparable with the reactor failure and may result in radioactive contamination of the environment.

The transfer of the ^{137}Cs radioactive nuclide has been simulated at hypothetical ZNPP failure under meteorological conditions as of 23 to 25 August, 2022. On these days, as a result of the warfare on the ZNPP site, and fires of the Zaporizhzhia thermal station's ash dumps, two-time disconnecting of the 750 kV overhead circuit "Dniprovs'ka" took place. Three other communication links had been damaged earlier due to bombardments by the army of occupation. Eventually, the ZNPP energy unit No 5 was cut out from the mains, the disaster protection was actuated, and the energy unit No 6 was transferred to self-energizing conditions. In this way, the actions of invaders have brought about the total blackout of the ZNPP for the first time in its history.

Fig. 3 shows the map of fires that took place as a result of the warfare in the ZNPP area for the period from 23 to 25 of August, 2022.

The processing of ^{137}Cs emission data for the hypothetical ZNPP failure has resulted in mapping the concentrations of this radionuclide in the air and its fallout on the soil.

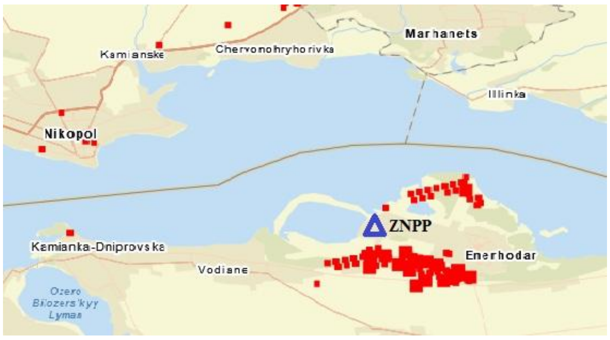

Fig. 3. Map of fires on 23 to 25 August, 2022, as a result of warfare in the ZNPP area. The zone of fires is marked red

Fig. 4 presents the map of ^{137}Cs concentration in the air on 23–25 August, 2022 (emission mass – 15 kg, general duration – 72 h, source height – 20 m). The emission plume is directed toward the north-west; therefore, it is the Ukraine's area that would be contaminated with ^{137}Cs. Besides, radioactive impurities could be partially carried over to the areas of the neighboring countries. According to the simulation data, during 23 to 25 August, 2022, the highest ^{137}Cs concentration values may be observed within the Ukraine area, in particular, in the near-field zone, 50 to 100 km in radius, around the emission source.

Fig. 5 shows the map of ^{137}Cs fallout on the soil on 23–25 August, 2022 (emission mass – 15 kg, general duration – 72 h, emitter height – 20 m).

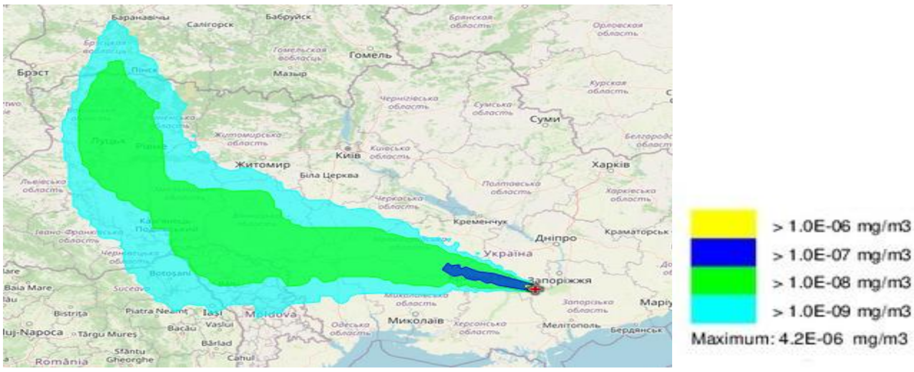

Fig. 4. ^{137}Cs concentration in air on 23–25 August 2022. General duration – 72 h, source height – 20 m

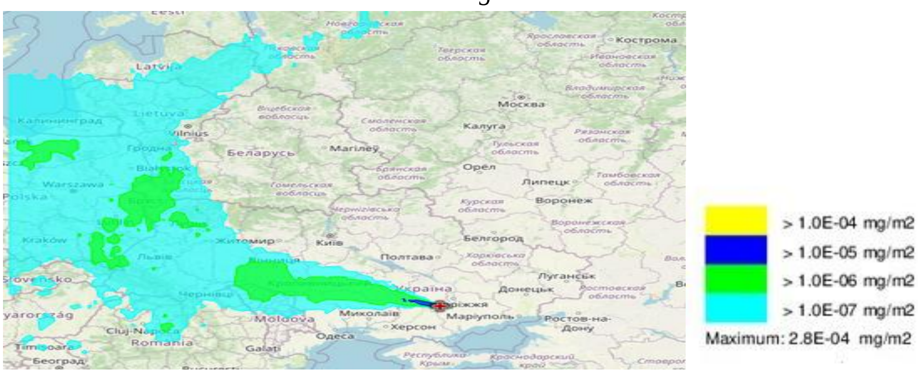

Fig. 5. Fallout of ^{137}Cs on the soil on 23–25 August 2022. General duration – 72 h, source height – 20 m

Since there was no way to determine exactly the characteristics of the emission source at the hypothetical ZNPP failure, the numerical simulation data should be interpreted only qualitatively and relatively.

CONCLUSIONS

Maps were developed for ^{137}Cs propagation in air and its fallout on the soil as a result of external extreme events in the ZNPP area on 23–25 August, 2022, which could provoke a radiation accident to occur. The undertaken analysis of ^{137}Cs radionuclide propagation has pointed to the supposed radiation pollution of the Ukraine area. Partially radioactive impurities might also be carried over to the areas of neighboring countries. According to the simulation data, during 23 to 25 August, 2022, the highest ^{137}Cs concentration values may be observed within the Ukraine area, in particular, in the near-field zone, 50 to 100 km in radius, around the emission source.

The situation concerned with the current radiation environment in the Ukraine area and with the potential sources of environmental radiation contamination is cardinally changing. This necessitates the revision of the radiation monitoring methodology, and also, the essential optimization of the existent observation network, laying emphasis on the transboundary radioactivity transportation by air masses and surface waters, in impact of the active nuclear power units, of radioactive waste handling facilities, of objects of uranium product manufacturing activities, etc.

The risks of occurrence of nuclear and radiation accident hazards under war conditions remain high and only the termination of RF military invasion and the restitution of absolute control by Ukraine over the ZNPP and other temporarily occupied regions can be a guarantee radiation safety for Ukraine, Europe, and the world.

REFERENCES

1. *A combined program of improving the power unit operating safety of Ukrainian NPPs (Ecological assessment statement, version 4)*. State enterprise NAEC " EnergoAtom", 2011, p. 340.

2. *Report on the nuclear and radiation safety status in Ukraine in 2022*. State inspectorate of nuclear regulation in Ukraine, 2022, p. 86.

3. V.K. Bronnikov, N.A. Verkhovetskiy, et al. *Zaporozhskaya NPP and the environment*. Kharkiv, 1994, p. 99.

4. M.F. Kozhevnikova, V.V. Levenets, V.N. Voyevodin. Validation of the Pollutant Source Identification Method Exemplified by the Environmental Impact of the Chornobyl Accident in the ZNPP Location Area // *Nuclear and radiation safety.* 2014, N 3, p. 52-58 .

5. *Nuclear technology review*. International Atomic Energy Agency, Vienna, 2017, p. 54 .

6. B.E. Paton, I.M. Neklyudov, V.S. Krasnorutsky. The future of atomic energetics determines the objectives of the nuclear fuel cycle in Ukraine // *Problems of Atomic Science and Technology*. 2013, N 5(87), p. 3-10.

7. A. Afanasyev, L. Gromok, V. Pavelenko, N. Steinberg. Radioactive waste management in Ukraine: Status, problems, prospects // *IAEA*. 2004, v. 35, p. 139-140.

8. *On adoption of Strategic lines of handling the spent nuclear fuel from Ukrainian atomic power plants with WWER-type reactors for the period up to the year of 2030 and Action Area Plans of their realization*: The Order of the Ukrainian Ministry of Energy and Coalmining No 386 as of 19.06.2015; https://ips.ligazakon.net/document/FN011418

9. V.G. Rudychev, S.V. Alyokhina, V.N. Goloshchapov, et al. *Safety of dry storage of spent nuclear fuel.* Karazin Kharkiv National University, 2013, p. 200.

10. S.V. Alyokhina. Elaboration of scientific-methodological principles for thermal safety of dry spent fuel storage in Ukraine // *Problemy Mashinobuduvannya*. 2018, v. 21, N 3, p. 4-12 (in Ukrainian).

11. S. Alyokhina, A. Kostikov, S. Kruhlov. Problems of modern nuclear power engineering safety issues of the dry storage of the spent nuclear fuel // *Problems of Atomic Science and Technology*. 2017, N 2(108), p. 70-74

12. S.V. Alyokhina. Thermal aspects of some emergency situations at dry spent fuel storage in ventilated containers // *Safety problems of atomic power plants and Chernobyl*. 2018, N 30, p. 24-30; doi.org/10.31717/1813-3584.18.30

13. S.V. Alyokhina. Heat transfer conditions in the dry spent fuel storage container of power reactors // *Elektrotekhnika ta Elektrotenergetyka*. 2018, N 2**,** p. 29-37 (in Ukrainian).

14. *Nuclear Safety, Security and Safeguards in Ukraine: Summary Report by the Director General, 24 February – 28 April 2022.* IAEA, Vienna, 2022, p. 26; https://www.iaea.org/sites/default/files/22/04/ukraine-report.pdf

15. *Nuclear Safety, Security and Safeguards in Ukraine: Summary Report by the Director General (as of 5 June, 2023).* IAEA, Vienna, 2023, p. 33; https://www.iaea.org/sites/default/files/23/09/gov2023-44.pdf

16. *Nuclear Safety, Security and Safeguards in Ukraine*: Summary Report by the Director General (as of 5 September, 2023). IAEA, Vienna, 2023, p. 33; https://www.iaea.org/sites/default/files/23/09/gov2023-44.pdf

17. *The Fire Information for Resource Management System (FIRMS);* https://firms.modaps.eosdis.nasa.gov/

18. R.R. Draxler, G.D. Hess. *Description of the HYSPLIT-4 Modeling System.* Silver Spring: Air resources Laboratory, NOAA Technical Memorandum ERL ARL-224, 1997, p. 22; https://www.arl.noaa.gov/documents/reports/arl-224.pdf

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МОДЕЛЮВАННЯ ПОШИРЕННЯ РАДІОНУКЛІДІВ ПРИ ЗОВНІШНІХ ЕКСТРЕМАЛЬНИХ ПОДІЯХ У ЗОНІ АЕС

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На сучасному етапі розвитку енергетичної галузі України все більшої актуальності набувають питання енергобезпеки та енергонезалежності країни. Лідером у вирішенні проблеми поводження з відпрацьованим ядерним паливом (ВЯП) в Україні стала найбільша в Європі Запорізька АЕС (ЗАЕС), на території якої було створено найбільше в Європі сухе сховище ВЯП. Збройний конфлікт створює загрозу ядерній та фізичній безпеці в Україні. Починаючи з 24 лютого 2022 р. спостерігалася активізація військових дій у країні, а також активізація військових дій на ЗАЕС (4 березня 2022 р. російськими військами був захоплений майданчик ЗАЕС), що викликає занепокоєння щодо потенційного впливу цієї ситуації на ядерну та фізичну безпеку під час експлуатації ядерних установок та проведення робіт, пов'язаних з радіоактивними джерелами. У роботі проведено моделювання поширення радіонуклідів при зовнішніх екстремальних подіях у зоні АЕС на прикладі ЗАЕС. Виконано моделювання перенесення радіонукліду ^{137}Cs при гіпотетичній аварії на ЗАЕС при метеорологічних умовах станом на 23–25 серпня 2022 р. Згідно з результатами розрахунків, протягом 23–25 серпня 2022 року найвищі значення концентрацій ^{137}Cs можуть спостерігатися у межах території України, особливо у ближній зоні від джерела викиду радіусом 50…100 км, а також радіоактивні домішки можуть бути винесені на території сусідніх держав.