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A Simulation to Assess the Probability of the Spread of Radioactive Materials from the Zaporizhzhia Nuclear Power Plant using the HYSPLIT Model

Behshad Valizadeh[1]✉ | Yassin Heydarizade[2] | Javad Tayebi[2] | Mohammad Reza Rezaie[2]

1. Department of Radiation Application, Shahid Beheshti University, Tehran, Iran.
2. Department of Nuclear Engineering, Faculty of Sciences and Modern Technologies, Graduate University of Advanced Technology, Kerman, Iran.

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ABSTRACT

Today, world pollution is increasing, and many pollutants such as radioactive elements enter to environment through human activity contaminants play an essential role in human life and health. Therefore, the examination of models for dispersion caused by radioactive substances is an important issue. This article is a simulation study of the hypothetical scenario of the Zaporizhzhia Nuclear Power Plant (ZNPP) in Ukraine, which is one of the NPPs in Europe. This scenario includes the occurrence of an accident in the power plant that entry of pollutants to environment and creates an environmental disaster. The simulation of this scenario was done using the Hyspli4)Hybrid Single-Particle Lagrangian Integrated Trajectory) model and NOAA website data of ZNPP (include the wind information, temperature, humidity, and atmospheric pressure in different spatial and temporal scales) to predict and deal with pollutants. The simulation was conducted in the first week of April 2023 for 131 I and 137Cs elements, which are important elements that come out of the power plant and cause many problems. The results show the highest annual dose and concentration are 4.6 mSv/year and 2.7E+06 Bq.s/m3 respectively. It also shows that in the event of pollution, the entry of contaminated materials into the Dnieper River and the western edge of the blackened sea will bring a great disaster. Also, the eastern and northeastern regions of Ukraine, especially Kharkiv and the western borders of Russia, lead to pollution that causes radiation hazard, so the news should be shared with everyone before an actual incident occurs.

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INTRODUCTION

Due to the growth of the population on the planet and, the limited fossil fuels, and the trend of life towards industrialization, today the world is inclined towards nuclear energy and has made good progress, at the same time, human concerns such as environmental pollution It can be hazardous for humans and animals (Pereira, Bašić et al., 2022). The production of electricity in residential and industrial areas requires advanced technology through fission in nuclear power plants (Mathew 2022). Controlled nuclear fission results in the release of a lot of heat (Zadfathollah, Balgehshiri et al., 2023). High heat produces water vapor and provides the necessary energy for the rotation of turbines and generators (Basem, Moawed et al., 2022). Generating electricity through nuclear energy has better environmental benefits compared by

*Corresponding Author Email: *b.valizade@Alumni.sbu.ac.ir*

fossil fuels (Murshed, Khan et al., 2023). The ZNPP in Ukraine is the largest NPP in Europe (Grechishnikov-Oskoma, Polukarov et al., 2022). This power plant with six nuclear reactors (Solovian 2023), each with a power of 950 MW (Lorenz and Nowak), is located in the southeast of Ukraine and near the Dnieper River (Molhem 2023). In extreme cases, the chimneys of these NPP may release large amounts of radioactive materials into the atmosphere due to nuclear accidents such as military attacks (Burke 2022), earthquakes (Tsuboi, Sawano et al., 2022), floods (Kubo, Jang et al., 2023), technical system failures, and human error (Ahn, Bae et al., 2022). These long half-lives radioactive elements with the alpha, beta and gamma ray emission (Bagher, Vahid and Mohsen 2014), by entering the atmosphere in large quantities from the chimney of the ZNPP under abnormal conditions, cause severe and destructive pollution of the atmosphere, soil, water, plants and animals (Shchipalkina and Smirnova 2023). When an accident occurs in the NPP, the first people exposed to this pollution are the residents around the NPP, the employees, the animals in the area and the environment (Yamashita and Suzuki 2013), (Iqbal, Howari et al., 2021). The release of radioactive materials in the environment causes many problems, such as cancer or affecting the genetics of people in the next generation (Brooks, Conca et al., 2023). In addition to causing chemical poisoning, radioactive materials may stick to smoke, dust, or fog (Imamura, Katata et al., 2020) in the air and fall on the ground as rain (Saber, Somjunyakul et al., 2019), contaminating groundwater and agricultural products (Singh, Bhadange et al., 2023) or entering the human body and settling in a particular part of the body. The removal rate of these elements depends on the properties of the isotope and its half-life and causes serious damage to the target tissue. Since nuclear energy has high economic benefits, it is equally dangerous and poses risks to the environment (Bandyopadhyay, Rej et al., 2022) and humans (Nematchoua and Orosa 2022). Choosing a suitable and cost-effective place to build an NPP is one of the most critical issues builders should consider (Abdullah, Shafii et al., 2023). Adverse weather conditions like severe storms can transport water vapor containing radioactive nuclei to other geographical areas (Marzo 2014). This is one of the tremendous examples of environmental damage. Ionizing materials and radiation from nuclear reactor leaks can cause serious risks to human health and the environment (Okano, Rosenberg et al., 2022). Ionizing materials in nuclear fuel that leak out due to accidents such as earthquakes, war, or lack of proper filtration in the chimneys of NPP, when they come into contact with water or air, can cause corrosive chemical reactions and Create a poison. These reactions can produce harmful gases. Ionizing substances in nuclear fuel that leak out due to events such as earthquakes, war, or lack of proper filtration in NPP chimneys can cause corrosive chemical reactions and create poisons when in contact with water or air. Radioactive elements can be carried into the air and transported to other areas through wind or storms and water. Some of these elements such as ^{131}I, ^{133}Cs and ^{137}Cs can quickly spread in the air and be inhaled by humans and animals. (Siraz, Roy et al., 2023). These radioactive elements can cause cancer or infertility. Ionizing radiation caused by nuclear reactor leaks can directly or indirectly harm humans and the environment. Direct radiation, such as gamma rays, can cause genetic changes, cancer, or death by irradiating living tissue (Zheng, Zhu et al., 2023).Direct radiation, such as gamma ray, can affect humans and other living organisms (Zheng, Zhu et al., 2023). These rays can reduce the immune system (Lumniczky, Impens et al., 2021), gland dysfunction (Jasmer, Gilman et al., 2020) or blood diseases (Xu, Peng et al., 2012). It is necessary to take proper safety measures to avoid the dangers of materials and ionizing radiation caused by leakage in a nuclear reactor (Obaidurrahman, Arul et al., 2021). These measures include the design and construction of nuclear reactors with high standards, continuous monitoring and control over the operation of the reactors, the implementation of training programs and preparedness for facing nuclear accidents, and the creation of information and warning systems for the public in case of leakage or It is a nuclear explosion. Choosing the right place to construct NPP (Kiomarsi, Shojaei and Soltani 2020), using advanced technologies to protect NPP and chimney ventilation, and predicting weather conditions and the path of dispersion of nuclear pollutants in the atmosphere can reduce the damages mentioned. As a result, having a model to investigate and predict such incidents requires using different air pollution models. Today, there are many models and software to determine air pollution, and modeling is one of the most advanced tools used to predict the state of air pollution. It shows how radioactive materials are released, their location, and their concentration. Hysplit4 is one of the most essential software in forecasting air pollution (Lichiheb, Hicks et al., 2022). The purpose of this article is to predict the pollution caused by a hypothetical accident in the ZNPP, which caused the spread of radioactive materials to the environment outside the reactor, and the pollution of the surrounding areas of this power plant is checked using Hysplit4 software for April 2023.

MATERIAL & METHOD

In this article, Hysplit4 software is used to check the level of pollution in the area around the ZNPP. First introduces Hysplit4 software and how it simulates. Then it was discussed the how extraction meteorological data from reliable sources and how application it to Hysplit4 software. finally, the method of extraction results related to the distribution of radioactive elements and the technique of extracting dosimetry calculations in Hysplit4 was explains in following.

Hysplit4 software

The Hysplit4 model is an advanced and multipurpose model for modeling the transport and changes of atmospheric pollutants developed by the National Oceanic and Atmospheric Administration (NOAA). Using the entered metrological data, this model can calculate and display the path of movement, concentration and deposition of contaminants in different spatial and temporal scales. This model uses Eulerian and Lagrangian methods to model the transport of pollutants and to model the initial release of contaminants from the source. Also, the modeling of physical and chemical processes of radioactive materials and selecting appropriate calculation parameters for simulation have been used. Euler's method is based on solving the equations governing the atmospheric flow in finite spatial and temporal grids. The Lagrangian method is based on tracking virtual particles that represent pollutants. These two methods are combined and form the Hysplit4 model. Previously, the ability of Hysplit4 software to simulate air pollution in real conditions has been investigated, and its practical results have been compared with simulation results and the accuracy of Hysplit4 software results has been confirmed (Choi Y, et al., 2020). Therefore after Hysplit4 confidence, the results of a hypothetical test can be used to prevent pollution caused by the spread of radioactive elements and radiation hazards for living organisms around a power plant after event of an accident in real condition.

ZNPP

ZNPP in Ukraine near Enerhodar city has six light-water nuclear reactors. Each reactor's production capacity is 950 MW [8] or 5700 MW total output power. The construction of an NPP in Ukraine was chosen because the land is unsuitable for agriculture. According to Table 1, the 10,000 pollutant particles released from the reactor and tracked by the model. The simulation starts from April 1, 2023, to April 7, 2023. The location of the pollutant source was considered using Google Earth. The total amount of radioactive materials released from the source was 1000 Ci. The type of pollutant considered was ^{137}Cs and ^{131}I.

Scenario of Hypothetical Accident ZNPP

It is assumed that if occurs an incident such as a military attack, a bomb explosion, the power plant's safety systems incident, etc., A large amount of radioactive nuclei releases into the environment. These incidents can lead to water and cooling system interruptions and cause

Table 1. The information related to the number of primary particles, initial amount of pollutants, type of pollutants, physical and biological half-life, height above the ground, and location of the ZNPP

Height (above of earth surface)	Activity of initial amount of Pollutant	Pollutant Type	Physical Half-Life	Biological Half-Life	Number of particles	Location
100 m	1000 Ci	^{137}Cs, ^{131}I	^{137}Cs(30 y) ^{131}I(8.1 d)	^{137}Cs(78 d) ^{131}I(138 d)	10000	47.51 N 34.59E

technical defects in the reactor core's operation and melting it. In this case, many radioactive materials around the NPP enter the environment. According to the weather conditions around the NPP, this pollution is quickly transferred to different places. Those pollutions create radiation hazards, which require meteorological data to investigate these hazards.

Meteorology data

American meteorological data from the NOAA website are include the wind information, temperature, humidity, and atmospheric pressure in different spatial and temporal scales. Using the geographic data of the ZNPP, this data was received with a spatial accuracy of 0.5 degrees and a time accuracy of 6 hours from April 1, 2023, to April 7, 2023.

Hysplit4 model

To run the simulation, Hysplit4 software was used on the NOAA website. It is assumed that the release of radioactive materials on the first day is more than on other days; over time, the amount of radioactive materials gradually decreases according to the half-life. Radioactive elements released from the NPP are stopped at different heights according to their energy, half-life, and wind speed. To check the spread of air pollutants, the conditions of every day should be checked. The time and duration of the accident, and weather systems such as rain and wind can affect the spread of radioactive materials and spread them to distant areas and cause more pollution (Kaviani, Memarian and Eslami-Kalantari 2021). Different radioactive materials such as ^{131}I, ^{90}Sr, ^{137}Cs, ^{134}Cs, ^{239}Pu, and ^{3}H can leave the NPP and enter the environment. ^{131}I and ^{137}Cs are the most critical elements that can be released after an accident. This article considers the first week of April 2023 for the ZNPP. According to the weather systems and the Hysplit4 model, it is possible to predict the spread of pollutants caused by the ZNPP. The less meteorological data used to simulate the model, the less time it takes to run the software. These data have special formats that must be changed to use them. Using the software (FileZilla), meteorological data for April 2023 is downloaded and simulated. To analyze and predict the possible accident, the geographical coordinates (34.59 E , 47.51N) are entered so that the desired model is focused on the ZNPP. The simulation starts from April 1, 2023, to April 7, 2023. It is assumed that a possible accident occurred in the first week of April 2023, and the amount of radioactive pollution leakage in the surrounding areas and the atmosphere is monitored for one consecutive week. Since the data is specific to geographic coordinates, the wind direction and air movement (Trajectory) are checked in the first stage. The next step is to show forward trajectories from the first week of April, showing forward trajectories using GDAS data from April 1, 2023. According to the steps mentioned, radioactive materials' diffusion and dispersion paths were obtained using Hysplit4 software. After simulating the program and displaying the concentration, the amount of radiological dose and the concentration graph based on latitude and longitude were drawn using the software. Finally, the radiobiological dose is calculated using software, and the results will be compared with ICRP limit (Protection 2007). The values of different doses in terms of mSv/h are obtained for the areas in the path of dispersion of radioactive materials and the activity of radioactive elements around the NPP. Weather conditions such as rain, snow, wind speed, and direction can easily affect calculations and cause changes in concentration calculations. Weather conditions are different during the year, and it is possible to determine the most spread and place of pollution according to the amount of pollution and the time of release of radioactive substances in the environment.

Accuracy of Hysplit4 software

To evaluate the accuracy of the Hysplit4 simulation, the results of a similar simulation for another power plant can be validated before doing it for the ZNPP(Abbasi, Zakaly and Almousa 2023). The results showed that the Hysplit4 model can predict and track radioactive substances in the air (Vali, Adelikhah et al., 2019). This model is also suitable for areas far away from the emission site but may have little accuracy. However, in the case of a nuclear emergency, this model can be efficient.

RESULTS AND DISCUSSION

To get the results using the Hysplit4 program, the coordinates of the ZNPP extracted from Google Earth that shown in Figure 1.

Using the meteorological data of the first week of April 2023, it was tried to calculate the path of the spread and dispersion of radioactive materials on the assumption after hypothetical accident that the results of which are shown in Figure 2.

Fig. 1. ZNPP situation with its coordinates

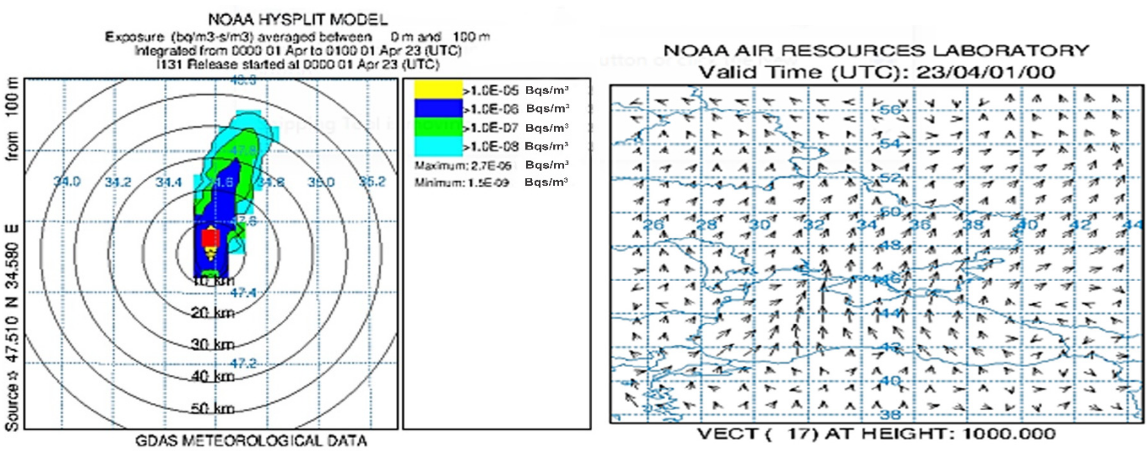

Fig. 2. Right: The direction of wind movement Left: The activity of radioactive elements released from the ZNPP in the first week after April 1, 2023

The spread path is 100 to 400 km from the ZNPP and is separated by six circles with 30 km interval. From 10 to 30 m from the ground's surface, the scattering path has been for one week from 1 to 7 April 2023. Up to less than 10 km, they have been exposed to radiation. According to Figure 2, the radioactive materials has penetrated less than 10 km after a week. Continuous contact areas up to 10 km have been found for ZNPP. The path of spreading radioactive materials from 10 to 50 km from the ZNPP is separated from each other by six circles, with a length of 10 km. Figure 3 shows the number of times a contaminant particle passes through a specific grid cell, the path of distribution and dispersion of radioactive materials, and the concentration of areas contaminated with radioactive materials.

Figure 4 shows the doses of radioactive materials in terms of mSv/hour at a distance of 10 to 30m above ground surface and the air concentration chart. It shows the maximum and minimum dose are 4.6 mSv/h and 1.2E -06 mSv/h respectively.

The number of radiobiological doses is shown in Table 1. It is more than when the ZNPP is in normal mode. The farther away from the accident area, the release of radioactive materials is small, and the closer to the accident site, have the high activity and high dangerous effects of

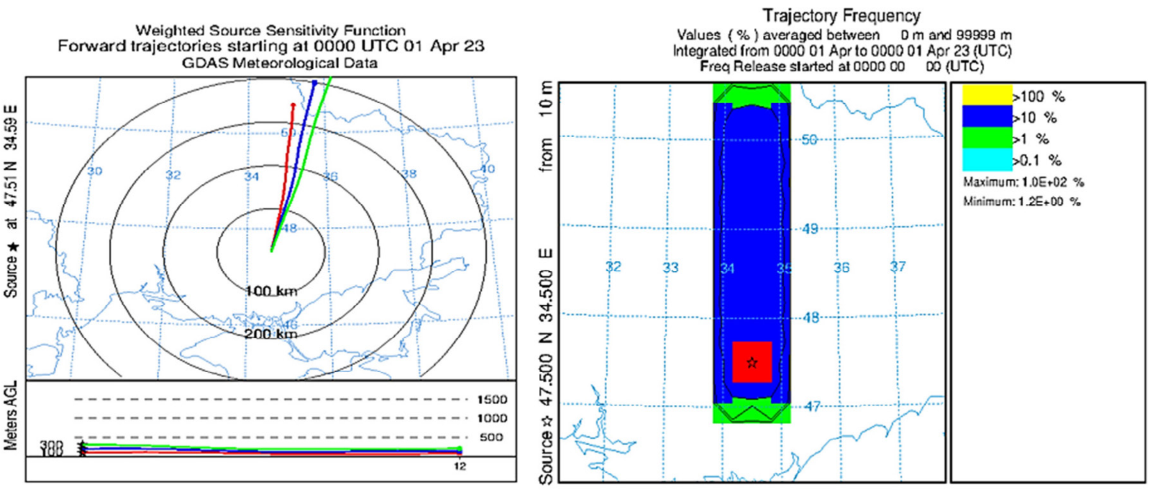

Fig. 3. Frequency path and the concentration of radioactive materials for ZNPP up to a height of 100 m

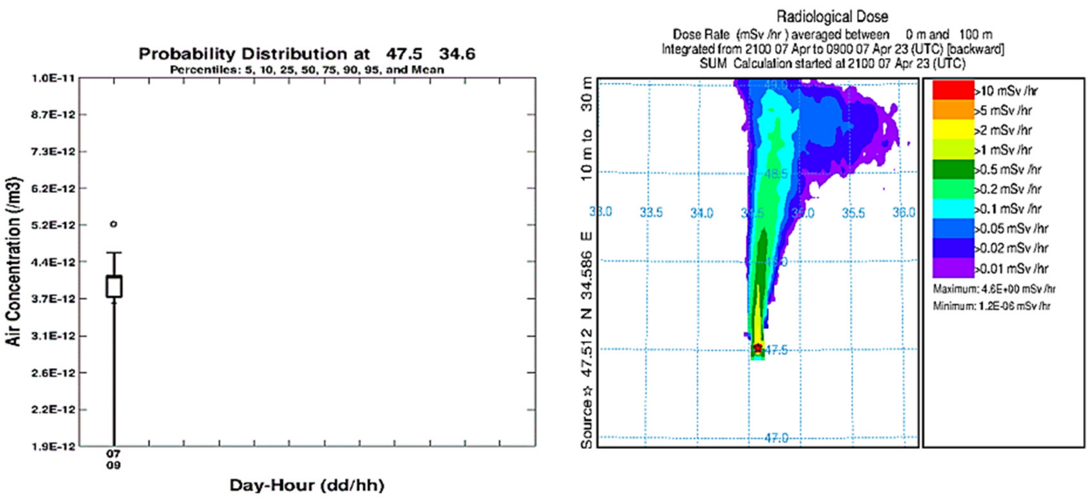

Fig. 4. Radiological dose and spread of radioactive substances in different areas and Air concentration chart by Day-Hour (dd/hh).

Table 2. Radiological dose of ZNPP)mSv/h(

Radiological Dose mSv/h	**10**	**5**	**2**	**1**	**0.05**	**0.01**	**4.6**	**1.2**
Radiological Dose mSv/year	8.76E4 Close to ZNPP	4.38E4	1.75E4	8.76E3	4.38E2	1.75E2	8.76E2	1.05E-2 Far away from ZNPP

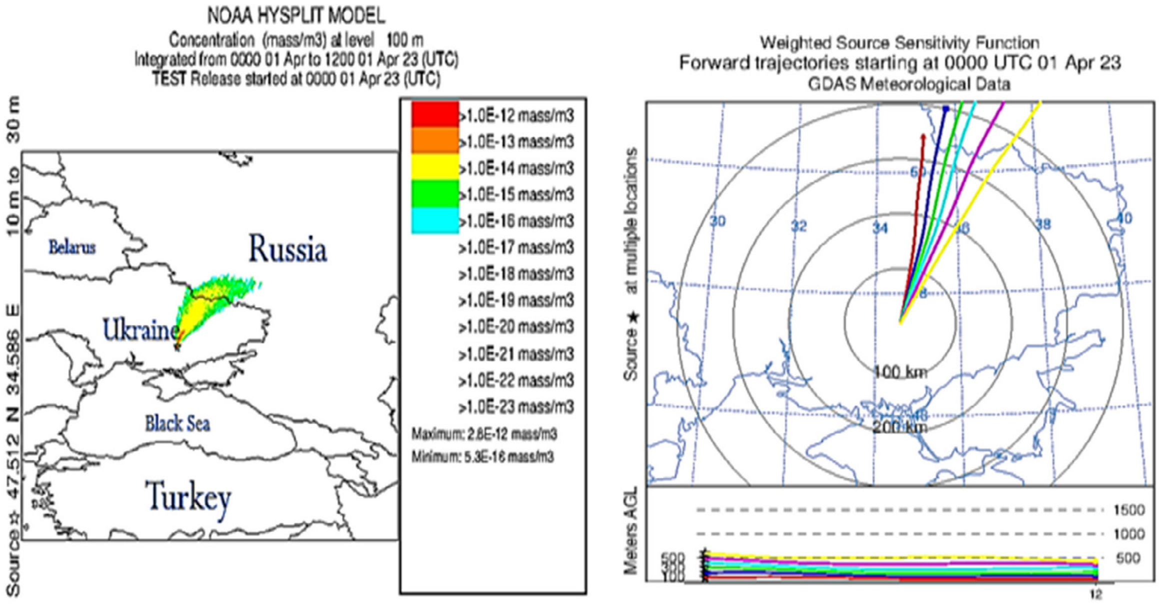

Fig. 5. Concentration of radioactive materials in different areas around ZNPP

radioactive materials.

According to Figure 4 data, the radiological dose for points far away from the ZNPP and the points near the ZNPP have been investigated, and result was shown in Table 2.

Table 2 data was shown that the annual dose only for points far away from the NPP is 1.05E+2 mSv/year that is lower than the ICRP annual limit (5 mSv/year). For places near the ZNPP, the dose is very high (8.76E+4 mSv/year) that is larger than the ICRP annual limit (Protection 2007).

Figure 5 shows possible accident of the six reactors of the ZNPP, which rapidly releases radioactive materials in the east and northeast of Ukraine and contaminates those areas, having the highest concentration up to 100 m above the ground. According to Table 3, the values of the maximum dose and the maximum concentration of contamination were obtained using Hysplit4 software, and these values are shown in different colors for Figures 2 and 4.

Figure 6 shows a graph of energy of radioactive elements in case of a possible accident for the ZNPP and its surroundings. According to the Figure 6, radioactive elements such as ^{137}Cs, ^{133}Cs, and ^{131}I was more active than other elements. Figure 5 shows due to the possibility of a malfunction in the ventilation system of the chimneys or the occurrence of any accidents, the people of the city of Zaporizhzhia, with a population of 770,411 people and the city of Kamianka-Dniprovska with a population of 12,332 people may see a lot of damage due to exposure to radiation from the ZNPP. The entry of radioactive radiation into the Dnieper River near the ZNPP and its path to the Black Sea can cause an environmental and human disaster.

Spreading radioactive elements in the environment and being placed on the soil and

Table 3. Maximum dose (mSv/h) and maximum concentration (Bq.s/m^3)

Maximum concentration (Bq.s/m^3)	Maximum Dose (mSv/h)
2.7E-06	4.6E+00

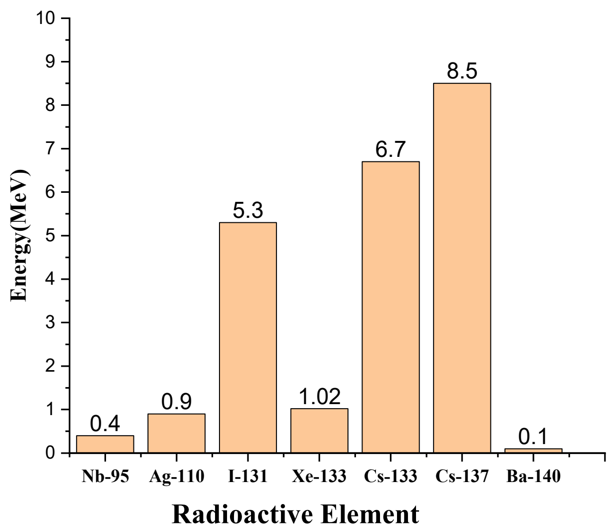

Fig. 6. Energy of radioactive elements in areas near the ZNPP

agricultural products, including livestock and dairy products, causes pollution and may even penetrate the underground layers with rain and contaminate the underground water. According to the results, the eastern and northeastern regions of Ukraine, especially Kharkiv, as well as the western borders of Russia, cause more pollution than other. Also, the entry of radioactive radiation into the Dnieper River near the ZNPP and its route to the Black Sea can lead to environmental and human disasters. Wind can be important in transporting and distributing these substances in the atmosphere. Radioactive materials may be carried to distant areas or neighboring countries or fall to the ground depending on the wind's direction, speed, height and season. The results of this article are similar to Bezhenar, R and et al (Bezhenar and Kovalets 2022) and was shown the radioactive elements pose environmental and cause health risks for humans, animals and plants. It is necessary to take preventive and control measures to prevent and reduce these risks. The constant contact of cities is in the path of distribution of radioactive materials, as well as cities and villages along the Dnieper River and all countries bordering the Black Sea. Both the Black Sea and the countries that have a coastline with the Black Sea are not safe from this environmental disaster. As a result, proper measures must be taken before such accidents occur in ZNPP to be done for prevention. Since the ZNPP is the largest NPP in Europe, if necessary measures are not taken to secure it, a bigger disaster than Chernobyl will happen.

CONCLUSION

This article simulates the Zaporizhzhia Nuclear Power Plant (ZNPP) in Ukraine by Hysplit4 software after an incident that case by war (Kurando 2023), earthquake etc. The reason for simulating with the Hysplit4 model is that this model examines the possibility of performing advanced Lagrangian equations for calculating radioactive elements movement path, concentration, pollution location, and wind path to remote areas. Since this program may have errors, this software is suitable for use in model simulation. After occurrence of an accident, the radioactive elements such as ^{131}I and ^{137}Cs entry to the environment. The simulation was study the behavior of ^{131}I and ^{137}Cs in environment around ZNPP after the first week of April 2023. The results obtained in this article show the highest activity and annual dose of above elements are 2.7E+06 Bq.s/m^3 and 4.6 mSv/year respectively. Since ^{131}I and ^{137}Cs are dangerous elements, and their effects depend on the duration of radiation exposure, the physical resistance and the Half-life, released from the chimney of the power plant during an accident, cause many problems, as ^{137}Cs in a low radiation dose leads to damage to the thyroid but does not lead to cell death, and ^{131} I in a high dose of radiation causes more damage to the thyroid and even cell death or causes thyroid cancer**.** Since radioactive materials may go into the underground water, contaminate agricultural products and animals, and cause significant environmental risks. Predicting these hypothetical events before the main event can help reduce of radioactive hazards. Therefore, the ZNPP must implement adequate safety measures and emergency plans to prevent or reduce the consequences of a severe accident. It also shows that the entry of contaminated materials into the Dnieper River and the western edge of the blackened sea will bring a great disaster. Also, the eastern and northeastern regions of Ukraine, especially Kharkiv and the western borders of Russia, lead to pollution after an incident in ZNPP.

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The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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