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MUTUAL TRANSBOUNDARY RADIATION IMPACT OF NPPS IN UKRAINE AND NEIGHBORING COUNTRIES: ANALYSIS, FORECAST, AND CONTROL

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A study was conducted to generalize the analysis of the results of previous studies by the authors devoted to assessing the mutual transboundary impact of nuclear power plants of Ukraine and neighboring countries. The main attention was paid to radiation impact in cases of normal operation and possible beyond-design-basis accidents. The distribution of radionuclide concentrations, annual radiation doses and risks to the population for a period of 50 years was performed using the PC COSYMA and HotSpot software packages, taking into account the most adverse meteorological conditions that determine the scale of potential radiation contamination of territories in a transboundary context. The maximum radiation doses for adults on the border of Ukraine do not exceed the permissible dose limits under the conditions of normal operation of NPPs of Ukraine and Europe and in the event of a beyond-design-basis accident.

INTRODUCTION

The article is dedicated to the bright memory of Vitko Valeriy Ivanovych, Candidate of Physical and Mathematical Sciences, a well-known specialist and scientist in the field of radiation monitoring, modeling, environmental impact assessment and environmental forecasting, who made a significant contribution to the development of radiation safety of energy facilities, in particular nuclear power plants. The author team expresses deep gratitude and respect for his many years of scientific work, professionalism and invaluable contribution to the preparation of this article. His experience, ideas and scientific vision of the problem became an important basis for the results presented in the work.

The results obtained are based on calculations using the PC COSYMA and HotSpot software packages and previously published author's materials, which allow forming a scientifically sound assessment of current and prospective risks of transboundary radiation impact [1-9]. The presented analysis can be used to improve the radiation monitoring system, predict the consequences of accidents and increase the level of radiation safety in Ukraine, especially in the areas around nuclear power plants.

In accordance with the requirements of the Convention on Environmental Impact Assessment in a Transboundary Context, ratified by the Law of Ukraine No. 534XIV of 19.03.1999 [10], as well as the requirements of Directive 2014/52/EU on the assessment of the effects of certain public and private projects on the environment [11] and Directive 2001/42/EU on the assessment of the effects of certain plans and programmes on the environment [12], a mandatory assessment of the environmental impact of the planned activity, including the impact in a transboundary context, is provided for. The provisions of these documents also apply to nuclear power plants.

The domestic radiation safety system is based on international standards, principles, criteria for ensuring radiation safety and radiation protection in relation to practical activities. It is developed in accordance with the main provisions of the Laws of Ukraine "On the Use of Nuclear Energy and Radiation Safety" [13], "On Radioactive Waste Management" [14], "On Human Protection from Exposure to Ionizing Radiation" [15], "On Licensing Activities in the Field of Nuclear Energy Use" [16], etc.

The provisions relating to ensuring radiation safety and protection against ionizing radiation are detailed in the Radiation Safety Standards (RSSU-97) [17] and the Basic Sanitary Rules for Ensuring Radiation Safety of Ukraine (BSRU-2005) [18]. In addition, dozens of special rules, norms and methodological documents are in force to organize and monitor the state of radiation safety in Ukraine.

The purpose of this work is to assess the impact of domestic and foreign nuclear power plants on the radiation situation on the border of Ukraine and compare the contributions of the studied nuclear power plants (NPPs) under the conditions of their normal operation and in the event of a beyond-design-basis accident (BDBA).

1. LOCATION OF THE STUDIED NUCLEAR POWER PLANTS AND CALCULATION POINTS ON THE BORDER OF UKRAINE

In the pre-war period (until 2022), four nuclear power plants with 15 operating units were in operation in Ukraine: Zaporizhia NPP – six PWRs-1000 units, South-Ukrainian NPP – three PWRs-1000 units, Khmelnytskyi NPP – two PWRs-1000 units, Rivne NPP – two PWRs-440 units and two PWRs-1000 units.

In Europe, the following NPPs nts are located near the border with Ukraine: the Czech Republic's nuclear power plants (Dukovany NPP – four units, PWRs-440/V-213, each with a capacity of 471 MW and Temelin NPP – two units PWRs-1000, each with a capacity of 1000 MW); Hungarian NPPs (Paks NPP − four PWRs-440 units with a total capacity of 1940 GW; Romanian NPP (Cernavoda NPP − two PHWR(CANDU-6) units with a total capacity of 1400 MW; Slovak NPP: Bohunice NPP − five PWRs-440/230 units with a total capacity of 1940 MW; Mochovce NPP − two PWRs-440/230 units each with a capacity of 470 MW; and Russian NPPs (Kurskaya − four HPCR-1000 units with a total capacity of 3700 MW; Novovoronegskaya − two PWRs-440/179 units with a capacity of 385 MW each, one PWRs-1000/187 unit with a capacity of 950 MW and two PWRs-1200/392M units with a capacity of 1114 MW each; Smolenskaya – three units with uranium-graphite channel reactors HPCR-1000, the capacity of each unit is 1 GW; Rostovskaya – four units, PWRs -1000/320 with a total capacity of 3800 MW).

Fig. 1 shows the location of NPPs in Ukraine, Europe, Russia, and control points on the border of Ukraine, where appropriate calculations have been made regarding the possible radiation impact on the population and the environment.

Fig. 1. Location of nuclear power plants in Ukraine, Europe, Russia and calculated control points on the border with Ukraine [1, 2]

2. IMPACT OF RADIONUCLIDE EMISSIONS ON THE BORDER OF UKRAINE UNDER THE CONDITION OF REGULAR OPERATION OF THE NPPS

All data on emissions are taken from the European Union Register [19], and used in the works [1, 3]. According to the calculations carried out by the authors, it was determined that the largest contribution to the annual dose is made by radionuclides H-3, C-14 [1–4].

The main contribution to atmospheric air pollution by radionuclides H-3 is made by Cernavoda NPP. According to the calculations, all the studied NPPs have relatively small emissions of C-14 compared to emissions of H-3. The total dose values are approximately the same along the entire border of Ukraine.

All calculated values of volume activities are quite small, which follows from the calculations of annual radiation doses. The total annual effective radiation doses at the border, which are due to the total volume activities of all emitted radionuclides from all studied foreign and Ukrainian NPPs under the conditions of their normal operation, are four orders of magnitude less than the quota established for nuclear power plants according to RSSU-97 (40 μSv).

Along the entire border line, the values of the total average annual fallout of radionuclides I-131 and Co-60 are approximately the same, with the exception of points on the border with the Russian Federation [7]. This can be explained by the fact that the Russian NPPs are located near the border with Ukraine, so relatively large values of the average annual fallout of these radionuclides were observed on the border [3, 19].

3. POPULATION EXPOSURE DOSES AND RISKS AT THE BORDER OF UKRAINE UNDER NORMAL NPPS OPERATING CONDITIONS

The total annual effective radiation doses and risks at the border of Ukraine under normal operating conditions of all foreign NPPs for the studied radionuclides H-3, C-14 are shown in Figs. 2, 3, respectively.

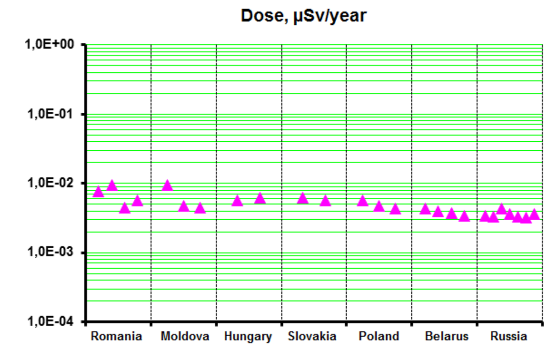

Fig. 2. Total annual effective doses for adults from all studied NPPs

The maximum annual effective doses for adults under normal operation of foreign NPPs can reach up to 9.4 nSv/year (see Fig. 2). This value is approximately three orders of magnitude lower than the quota established for NPPs according to the RSSU-97 (40 μSv/year). The maximum dose is expected at point 2 closest to the Cernavoda NPP on the border with Romania (130 km from the Cernavoda NPP).

It should be noted that the average annual effective dose of radiation to the population of Ukraine from all radiation sources is 2.4 mSv/year [4], therefore the additional contribution fromemissions from all NPPs under normal operation is negligible.

Thus, the average annual doses from the operation of foreign NPPs under normal operation are very small and do not pose a threat to the population.

Fig. 3 shows the value of the total annual risk of radiation for adults from radionuclide emissions from all foreign NPPs. Its dependence along the border of Ukraine repeats the dependence of the total dose. The risk values are negligibly small. It is worth noting that the dependence of the risk value on the distance along the border repeats the dependence for the two radionuclides H-3 and C-14, which make the main contribution to the dose.

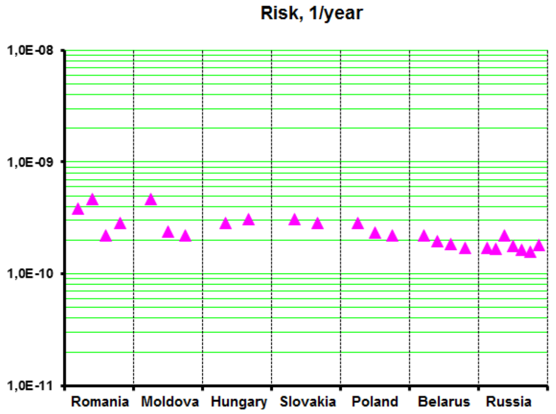

Fig. 3. Total annual exposure risk for adults from foreign NPPs

4. IMPACT OF RADIONUCLIDE EMISSIONS FROM FOREIGN NPPS IN THE EVENT OF A BEYOND-DESIGN-BASIS ACCIDENT

A beyond-design-basis accident (BDBA) is an event that goes beyond the design-basis conditions of a nuclear facility. A BDBA can have serious negative consequences for the population and the environment.

BDBA can be caused by a variety of factors, including events not considered in the design, multiple safety failures, or human error. Each such combination creates a unique scenario, the consequences of which cannot be averaged or reduced to a common denominator. Therefore, there is no exhaustive list of all possible types of BDBA at NPPs. They are by their nature unpredictable.

The calculation of the consequences of an emergency depends on the type of facility and the nature of the accident. In general, this is a complex task that involves the analysis of many factors. Special computer programs are used to analyze the emergency, which simulate different scenarios of events. This allows you to assess the possible consequences and develop accident management strategies. For nuclear facilities, where the consequences can be particularly serious, the calculation includes an analysis of radiological impact.

In nuclear power, safety analysis is based on conservative estimates that assume the worst-case scenario to ensure the highest level of safety.

The radiological consequences of the releases presented in this article are studied, as mentioned earlier, using computer programs for four Ukrainian and ten foreign NPPs. These plants have reactors of different types and capacities, they are located in regions with different meteorological conditions, which affect the characteristics of the spread of the cloud of different radioactive composition of the release. Therefore, to obtain results that could be compared with each other, the authors used a conservative approach, which considers the worst release of the key indicator of a serious accident for all NPPs, which is Cs-137. This makes it possible to assess the impact of different nuclear power plants on the environment and human health from the same perspective.

When determining the input of BDBA radionuclides in accordance with the safety requirements of the European Operating Organizations for light water reactor NPPs projects [20], the calculation was based on the limit value of the release of Cs-137 to the environment at the level of 30 TBq. The isotope Cs-137 was chosen because of its dominant value for long-term environmental pollution, as well as its impact on public health. The choice of meteorological conditions in emergency situations was made on the basis of calculations of radiation doses to the population, and the most unfavourable meteorological conditions were selected, under which the doses are maximum (conservative approach).

5. DOSES AND RISKS AT THE BORDER OF UKRAINE DURING BDBA

The authors have calculated the expected effective individual doses over 50 years and risks over the same period at calculation points on the border of Ukraine in the event of a BDBA, the consequence of which is a large release of Cs-137 compared to other radionuclides. It is important to note that the occurrence of BDBA at all NPPs at once is unlikely. The most likely event may be an accident at one of the NPPs. Therefore, in this case, based on a conservative approach, the maximum values of doses and risks were selected at each calculation point on the border of Ukraine. Figs. 4, 5 show the maximum values of doses and risks for each of the countries adjacent to Ukraine. These figures show that the value of the expected effective dose and risk over 50 years is maximum at the border with the Russian Federation.

In the NRBU-97, in the event of a radiation accident, there are instructions on the dose values at which it is necessary to take countermeasures to protect the population.

In our case, the dose of 1 Gy in 2 days according to the RSSU-97 instructions is not exceeded, because the total effective dose in 50 years is much lower.

All other dose values are greater than the maximum dose at a point on the border with Russia, which is 6.0 mSv in 50 years. For other states, the expected doses are even lower, so according to the RSSU-97, no intervention is required.

The average expected effective doses for the population after the BDBA for 50 years are small compared to the annual effective dose according to the RSSU-97, which does not exceed 1 mSv/year for the population.

The report of the UN Scientific Committee on the Effects of Atomic Radiation [21] indicates that the annual effective dose from natural radiation sources in regions with normal radiation background is 2.4 mSv, which is more than the average for BDBA at the studied NPPs.

It should be noted that relatively small doses are observed on the border of Ukraine, which are due to the large distances from it of almost all foreign nuclear power plants. The dependence of the risk magnitude on the distance on the border is the same as the doses, as evidenced by the data presented in Fig. 5.

According to calculations made for a distance of 425 km from the emission source, the largest contributions to the dose during the BDBA are given by cesium isotopes: Cs-134 – 66%, Cs-137 – 29% and Sr-90 – 2%. The total contribution of other radionuclides during the BDBA is less than 3%.

The largest contribution is expected from food consumption − 93%. Irradiation from clouds contributes less than 1%, Irradiation from the soil contributes 5%, and exposure due to breathing − 1%. The remaining exposure routes can be neglected.

The contribution of food products to the total effective dose is as follows: cereal products (62%), milk (10%) and meat (19%), vegetables (2%), potatoes (6%) and root vegetables (1%). The remaining food products make a combined contribution of less than 1%.

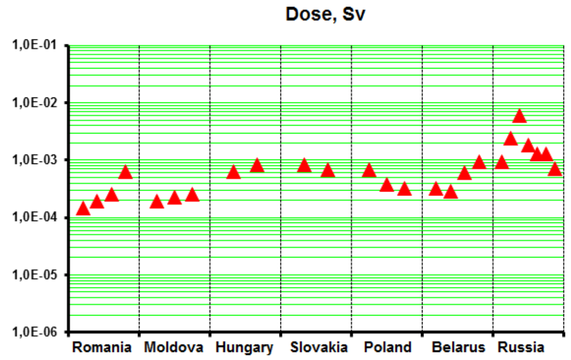

Fig. 4. Maximum effective doses over 50 years on the border of Ukraine with neighboring countries in the event of BDBA

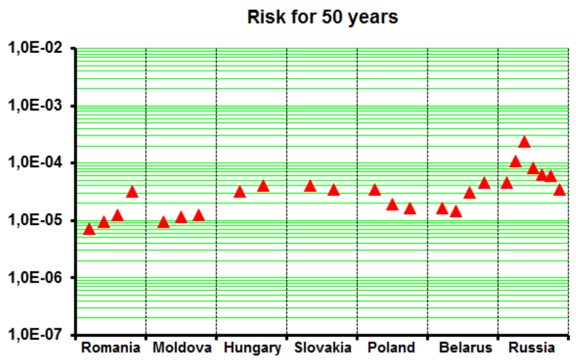

Fig. 5. Maximum risk value for 50 years at calculation points for BDBA

For different distances, the above contributions vary negligibly, but the main doses will be received from the fallout of Cs-134, Cs-137 and Sr-90.

6. COMPARISON OF MAXIMUM RADIATION DOSE VALUES AT THE BORDER OF UKRAINE

The maximum radiation doses at the border per year from nuclear power plants in Europe and Ukraine for the adult population under normal operating conditions are shown in Fig. 6

The level of dose values along the border is approximately the same. The doses from Ukrainian NPPs are higher, which is due to the proximity of domestic NPPs to the border.

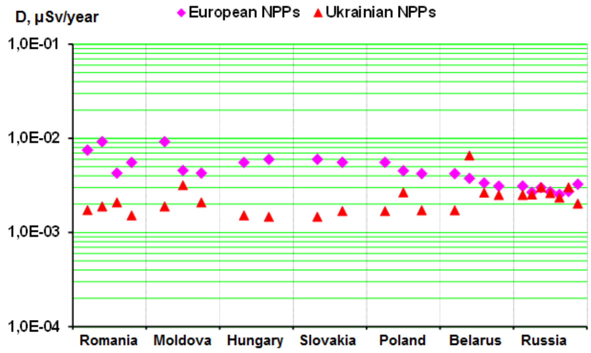

Fig. 6. Maximum radiation doses at the border of Ukraine per year from European NPPs for the adult population under normal operating conditions

For comparison, Fig. 7 shows the maximum radiation doses at the border from European and Ukrainian NPPs for the adult population in the event of a BDBA at one of the studied NPPs. In the BDBA, the same release conditions were set for each NPP. In this case, the magnitudes of doses and risks are entirely determined by the distance from the control point to the nearest NPP.

Ukrainian NPPs are located closer to the calculation points than European NPPs, therefore the radiation impact of Ukrainian NPPs generally exceeds the radiation impact of European NPPs. The exception is observed on the eastern part of the border with Russia Federation, where russian NPPs are closer to it and therefore their impact dominates [2, 3, 6].

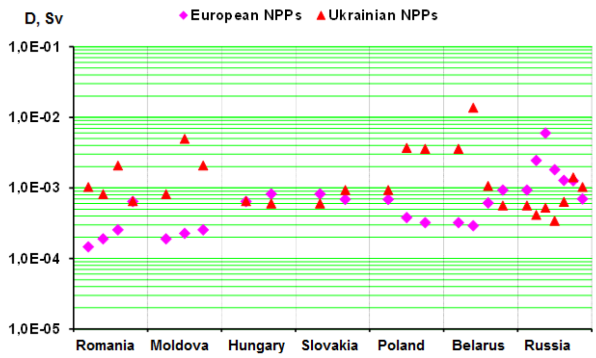

Fig. 7. Comparison of maximum radiation doses over 50 years for the adult population during a nuclear accident at one of the NPPs in Europe, Ukraine and Russia

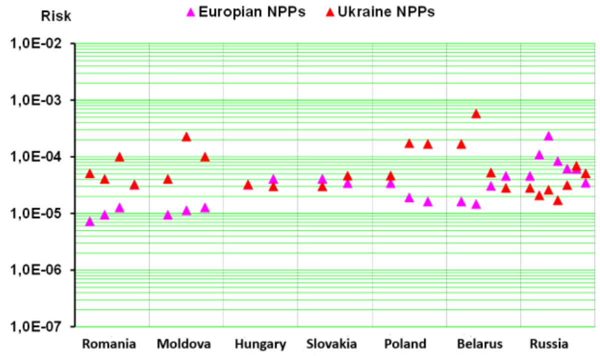

Fig. 8. Comparison of maximum risks over 50 years for the adult population in the event of a nuclear accident at one of the NPPs in Europe, Ukraine and Russia

Everything that was stated regarding the dependence of maximum doses on the location of points on the border of Ukraine is also true for risks (Fig. 8).

7. OFFLINE CONTROL OF TRANSBOUNDARY RADIATION IMPACT OF NPPS OF DIFFERENT COUNTRIES

As mentioned above, the results presented in the article are based on calculations that were obtained using the PC COSYMA and HotSpot software packages.

Of course, when analyzing with the help of computer programs the transboundary radiation impact of nuclear power plants of different countries, which have reactors of different types and capacities, located in regions with different meteorological conditions, which affect the features of the spread of the emission cloud of different radioactive composition, the authors were forced to apply different assumptions that allow us to consider this impact as the impact of emissions with the same characteristics under the worst possible scenarios of the development of emergency events.

This approach leads to large errors in the quantitative assessment of doses and risks. Therefore, the results presented in the article are rather illustrative and informative in nature. The forecast, formed on the assumptions, does not guarantee its accuracy, but can be taken into account when making decisions on ensuring radiation safety on the border of Ukraine, or on its entire territory.

The best option for obtaining a representative and accurate assessment of radiation parameter measurements both around NPPs and other radiation-hazardous facilities, as well as on the territory of the country and at the border, is radiation monitoring in real time, i. e. offline measurements. The authors propose to use for this purpose a network of control posts, which consists of a network of posts of departmental object automated systems and a network of non-automated atmospheric air radiation monitoring posts of the Ukrainian State Meteorological Center [22, 23]. It is recommended to perform predictive calculations of the impact of emissions (doses, risk) using special computer programs, for example, using the JRODOS program, which has been implemented in the national emergency response systems of many European countries, including Ukraine, and has proven itself well in practice.

In addition to ground-based monitoring systems or in combination with them, the authors propose the use of remote monitoring tools and technologies (UAVs, satellites), which are a powerful tool in the system of monitoring the state of atmospheric air and a necessary information base for creating air quality maps of the regions of Ukraine. Such data can be used to track changes in the radiation state of atmospheric air over different periods of time and for early warning of the population about changes in the radiation state on the territory of Ukraine, as well as on the country's border [24-26].

The use of remote monitoring technologies can ensure efficiency in data collection, and the creation of a single platform for collecting and analyzing data from ground stations and satellites or UAVs will contribute to more accurate and comprehensive environmental monitoring.

CONCLUSIONS

In accordance with international and national requirements for ensuring radiation safety, the article presents the results of the assessment of the environmental impact of the operation of Ukrainian and neighboring states on the border of Ukraine, which were obtained using the PC COSYMA and HotSpot software packages. The study assessed the level of radiation hazard of NPPs operation under normal operating conditions and in the event of radiation accidents.

Possible dose exposures and radiation risk have been calculated, which includes an assessment of population exposure doses and risks to public health during normal operation of the NPPs and in the event of accidents, including the transboundary nature of radiation exposure.

It is indicated that all calculated radiation parameters from emissions from nuclear power plants in Ukraine and Europe at the border during normal operation are very small.

The maximum dose values due to emissions from Ukrainian and European NPPs during normal operation are at the level of 10^{-3} μSv/year, which is approximately 6 orders of magnitude less than the average global annual dose due to natural radiation background and approximately 4 orders of magnitude less than the quota for Ukrainian NPPs.

For the BDBA, for which radionuclide emissions are considered under the worst-case emergency scenarios, the maximum values at the border of Ukraine in 50 years will be at the level of tens of mSv, which significantly exceeds the average global dose in 50 years from the natural background.

The results presented in the article are illustrative and informative in nature, since the predictive assessment of doses and risks, which is based on assumptions, does not guarantee its accuracy.

To obtain accurate estimates of radiation parameter measurements both around the NPPs and on the territory of the country and at the border, radiation monitoring should be carried out in real time, i. e. offline measurements. The authors propose to use a network of ground monitoring posts for this purpose, which consists of a network of departmental object automated systems posts and a network of non-automated atmospheric air radiation monitoring posts of the Ukrainian State Meteorological Center together with remote control means (UAVs, satellites), which will facilitate the prompt receipt of accurate radiation monitoring results.

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ВЗАЄМНИЙ ТРАНСКОРДОННИЙ РАДІАЦІЙНИЙ ВПЛИВ АЕС УКРАЇНИ ТА СУМІЖНИХ КРАЇН: АНАЛІЗ, ПРОГНОЗ ТА КОНТРОЛЬ

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Проведено дослідження щодо узагальнення аналізу результатів попередніх досліджень авторів, присвячених оцінюванню взаємного транскордонного впливу атомних електростанцій України та суміжних країн. Основну увагу приділено радіаційному впливу у випадках нормальної експлуатації та можливих запроєктних аварій. Розподіл концентрацій радіонуклідів, річних доз опромінення та ризиків для населення за період 50 років виконано з використанням програмних комплексів PC COSYMA та HotSpot із врахуванням найбільш несприятливих метеорологічних умов, що визначають масштаби потенційного радіаційного забруднення територій у транскордонному контексті. Максимальні дози опромінення для дорослих на кордоні України не перевищують допустимі ліміти доз за умови нормальної експлуатації енергоблоків АЕС України та Європи та у разі виникнення запроєктної аварії.