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Analyses of potential consequences after a severe accident in a RBMK-1000 during the Russia-Ukraine conflict

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Abstract:

The Russia-Ukraine conflict has significantly increased safety threats, primarily due to the potential damage to nuclear facilities like the VVER-1000 (Zaporizhzhya region), RBMK-1000 (Kursk region), and even research reactors. In response to the military activities near Zaporizhzhya and Kursk Nuclear Power Plants (NPP), assessments of the possible consequences of severe accidents have been conducted, considering the impacts across Europe. To simulate the radiological consequences, a combination of simulation codes, including SCALE and JRODOS, was employed. Initially, a geometrical model of the RBMK-1000 reactor was developed using SCALE. Subsequently, an engineering estimation methodology was applied to determine a source term, representing the fission products released from the damaged fuel assemblies. Next, large-scale atmospheric radionuclide release simulations were performed using the JRODOS software, where the release conditions were modeled based on postulated assumptions. The analysis of the radiological impact on European territories was conducted utilizing actual meteorological data obtained from the NOAA Operational Model Archive and Distribution System (NOMADS).

1 INTRODUCTION

The ongoing armed conflict between Russia and Ukraine has drawn attention to potential consequences that could result in severe accidents at Nuclear Power Plants (NPPs), leading to significant atmospheric releases of radionuclides. The global safety of NPPs can be therefore destabilized due to hazardous human-induced events through such risks as shelling, explosions, and other military activities. For this reason, areas with NPPs located in regions where the conflict appears to be escalating are under close observation across Europe.

In accordance with reports and press releases by the International Atomic Energy Agency (IAEA), the shelling of Zaporizhzhya NPP (ZNPP) first occurred in March 2022 [1] and has continued up to the present (autumn 2024) [2]. Regarding Kursk NPP (KuNPP), the first military activities involving drones were observed in October 2023 [3], with an escalation occurring in the summer of 2024 [4]. Damage of NPPs caused by the shelling may lead to a complete loss of all power sources. The failure of the power supply is one of the conditions can cause a long-term station blackout (LT SBO), potentially resulting in a severe accident [5]. The shelling of KuNPP may also result in direct damage to the reactor, or, in the worst-case scenario, which is the focus of this study. The proposed scenario anticipates the core melting and the subsequent atmospheric radionuclide release from one operated unit of KuNPP [6].

The primary objective of this work is to estimate the radiological impacts following a severe accident at the KuNPP, similar to previous analyses conducted for the ZNPP [7]. The assessments focus on the scope of potential protective measures and the adverse effects of surface contamination on the agricultural sector surrounding the KuNPP. Due to the increasing concern from the IAEA regarding the exposure of nuclear facilities to direct military actions, the State Office for Nuclear Safety (SUJB) requested the National Radiation Protection Institute (SURO) to initiate several analyses. These analyses are dedicated to estimating a potential source term and evaluating its impact locally and across Europe, with particular emphasis on determining whether such events could affect Czechia.

2 MATERIALS AND METHODS

2.1 RBMK Description

The KuNPP site consists of four RBMK-1000 reactors and two VVER-510 reactors. The two RBMK-1000 units are in operation, while the other two RBMK-1000 units are in a shutdown phase. Additionally, both VVER-510 reactors are currently under construction [8]. The RBMK reactor core (Figure 1) is constructed of closely packed graphite blocks (a total mass of graphite around 1700 tons) stacked into 2488 columns. All columns have axial openings for fuel (1661 channels), for control rods (211 channels), and for instrumentation (172 channels). In addition, 444 columns are positioned within the radial reflector, with the central holes filled by graphite rods [9].The fuel channel tubes are set into the circular passages. The passages consist of aligned central openings of the graphite blocks and stainless steel guide tubes of the top and bottom core plate structures. This arrangement ensures that the core region remains hermetically sealed [6,9].

The fuel cladding is made from zirconium and niobium alloy. An RBMK fuel assembly consists of two fuel bundles placed one above the other. Each fuel assembly contains 18 fuel rods, which are arranged in two circles around a carrying rod. Every fuel assembly is placed in a separate fuel channel, with a total uranium mass of approximately 110 kg per assembly [6,9]. The total uranium mass in the RBMK reactor is approximately 182.7 tons. The control rods are made from boron carbide B4C and aluminum, and are placed in the individual channels, which are independent from the channels with fuel bundles. The channels with control rods are cooled with water supplied by the system totally independent from the Reactor Cooling System. The pressure in the control rod channels remains close to atmospheric. The fuel channels together with graphite stack are placed inside the leak-tight reactor cavity [6,9].

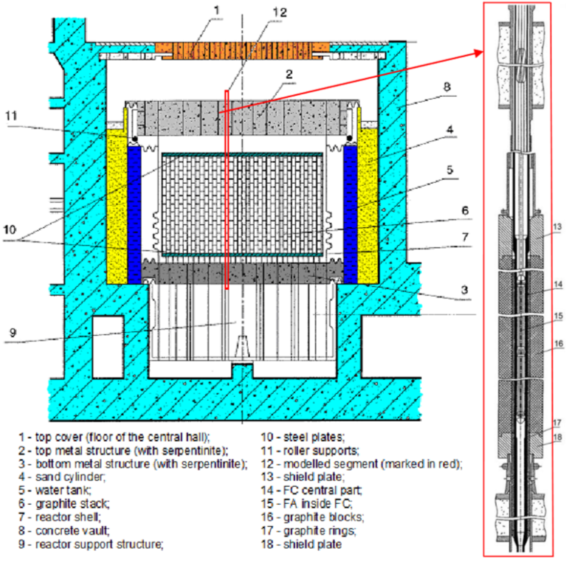

Figure 1. RBMK Core Layout [9]

2.2 Severe accident scenario

Employing published data about Ignalina NPP (two decommissioned RBMK-1500 units) [9,10], the RBMK-1000 mass inventory was estimated using the SCALE 6.2.4 code [11]. The TRITON sequence was utilized for neutron transport modelling. Based on the technical data provided within the WENRA community [12], the burnup for one RBMK-1000 unit of KuNPP was assessed. The campaign of 4.4 years was anticipated, or 1600 effective days of burnup per cycle, considering the constant load. In general, due to their lower power density, RBMK reactors have a low risk of undergoing a severe accident during a Loss of Coolant Accident or a Long-Term Station Blackout [9]. For this reason, the postulated severe accident scenario is initiated by damage to one operating RBMK-1000 unit. One of the weaknesses of the RBMK reactor is the absence of a containment structure capable of withstanding significant structural loads. Instead, the RBMK reactor utilizes building structures that serve the function of confinement. However, the confinement structure is not designed to endure heavy structural loads. Thus, the scenario assumes the destruction of the upper part of the reactor building. Another structural feature of the RBMK reactor is that the control rods are inserted into the reactor core from top to bottom, with the control rod drive mechanisms located at the top of the reactor [9]. As a result of the postulated event, the control rods would become inoperable, which could lead to the severe accident, including core melting [6]. Such accident can lead to a large-scale atmospheric release of radionuclides.

2.3 JRODOS scenario

Numerical simulations of the atmospheric dispersion of the released radionuclides were performed using the JRODOS tool, version 2019 [13]. Due to the absence of a severe accident model, the source term was determined through an engineering evaluation. The source term was based on 30% of the total inventory of one unit. Approximately 80% of the noble gases, 25% of the cesium isotopes, and 34% of the iodine from this radioactive material were released into the atmosphere [14]. The overall activity of the proposed source term was then 6.5E18 Bq. The total activity of cesium isotopes was 3.6E17 Bq. The amount of iodine isotopes was 1.9E18 Bq. The overall activity of noble gases was 3.4E18 Bq. Uranium and transuranium elements were not included in the source term due to the far-range simulations across European territories, with a calculation radius of up to 800 km. The release height was set at 300 m above ground level due to a fire in the core. The total release and prognosis duration was 7 d to meet the criteria for potential protective measures [15]. However, under real conditions, a longer release/prognosis duration may be required.

The models used in the simulations were the RIMPUFF dispersion model [16] and the “Emergency” model chain [13]. The simulations focused on total potential effective doses, thyroid equivalent doses and specific activities in wheat. The total effective doses were a sum of doses from deposition, cloud and inhalation (projected doses). For estimates of activities in the foodstuff (i.e., wheat), the model FDMT (Food Chain and Dose Module for Terrestrial Pathways) of JRODOS was used [17]. According to press releases from the IAEA and various news agencies, military activities in the vicinity of KuNPP intensified in August 2024 [18]. Thereafter, five time intervals in August 2024 were selected, and the scenario was simulated using the corresponding weather data. Meteorological data were provided by the NOAA Operational Model Archive and Distribution System (NOMADS) [19]. Additionally, several time intervals at the beginning of August 2024, **before harvesting** (default set-up in JRODOS), were tested to assess the activity levels in wheat.

Consequently, simulated maps of effective doses two and seven days after the release began, along with maps of thyroid equivalent doses and specific activity levels in selected crops, were extracted from JRODOS and evaluated. For each simulation, the maximum distance for the selected criteria was estimated to assess the range of potential countermeasures. Thereafter, the maps were additionally averaged to obtain rough orientational levels of the criteria of interest.

3 RESULTS AND DISCUSSION

3.1 Total effective and thyroid equivalent doses

Figure 2 presents the averaged map of total effective doses integrated over seven days after the release began. The source map was provided by OpenStreetMap contributors [20]. For the implementation of possible protective measures, Czech criteria were adopted [15]. However, the concept of projected doses was employed instead of averted doses due to the use of JRODOS. For sheltering and evacuation, projected doses of 10 mSv (integration over 2 days) and 100 mSv (integration over 7 days), respectively, were applied. In the case of iodine prophylaxis, a projected equivalent thyroid dose of 100 mSv was assumed. Considering evacuation (Figure 2), the corresponding area is approximately 10 km far from KuNPP. We would like to emphasize that this distance is based on the **averaged map**, while the actual distances for implementing all countermeasures will depend on the actual meteorological conditions. A range of the most distant areas from KuNPP based on **actual** weather conditions in August 2024, where all protective measures may be required, is listed in Table 1. However, in a real emergency case, all doses and the corresponding affected areas will be evaluated repeatedly, using actual prognoses. The scale of protective measures will be then proposed, in accordance with **local** regulations.

According to Table 1, areas around KuNPP may require sheltering and evacuation up to several tens of km following large atmospheric radionuclide releases. In the case of iodine prophylaxis, the scale of implementation may extend up to roughly two hundreds of km. This countermeasure should be applied based on the actual path of the radioactive cloud and the levels of thyroid exposure, rather than across the entire affected area. In accordance with the simulations results and the employed assumptions (the source term, meteorological conditions in August 2024, etc.), Ukrainian and Russian border territories, up to several hundreds of km from KuNPP, will be therefore primarily affected.

Patterns of radioactive fallout strongly depend on the weather conditions, especially precipitation [21]. Therefore, for other meteorological datasets, affected areas and the scale of protective measures may differ. Considering more distant areas (e.g. thousands of km from KuNPP), substantially lower doses can be expected, from hundreds of nSv up to tens of µSv, being below the criteria for protective measures [22].

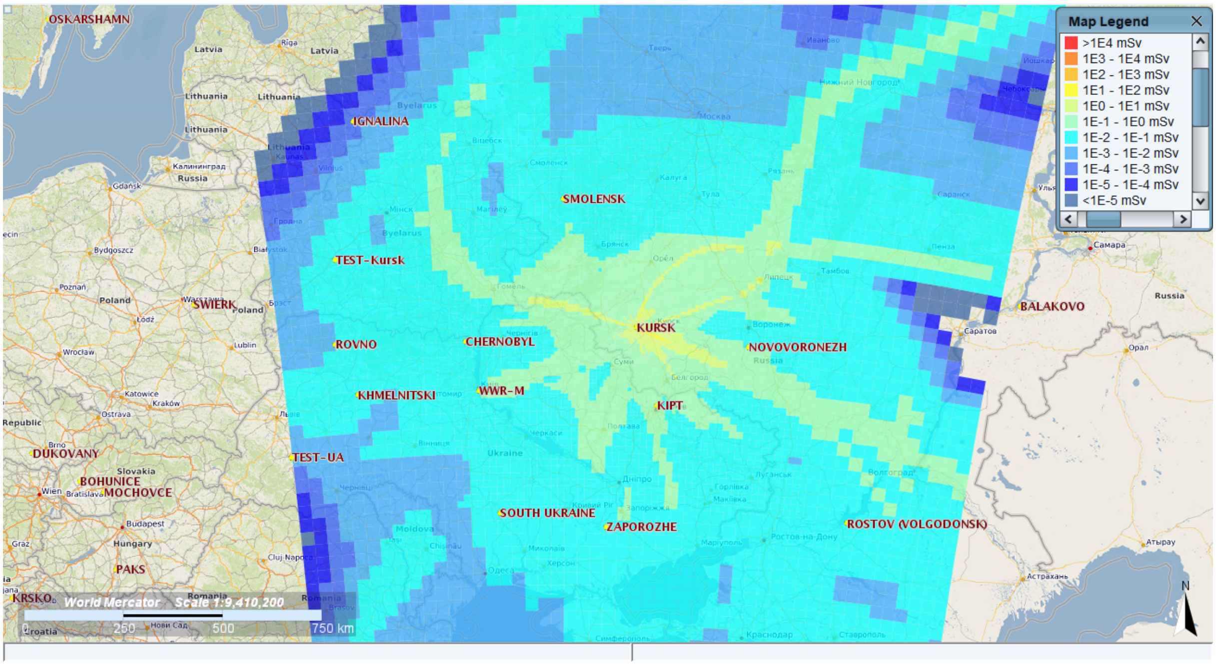

Figure 2. Averaged map of total potential effective doses over 7 days

Table 1. Scale of protective measures for weather conditions in August 2024

Protective measure	Dose level (mSv)	Maximum distance (km)
Sheltering	10	12–43
Evacuation	100	18–34
Iodine prophylaxis	100	101–197

3.2 Specific activities in wheat

Russia and Ukraine are among the most significant agricultural exporters in the world. In terms of wheat production, Russia and Ukraine are expected to be the fourth- and ninth-largest producers, respectively, in the 2023/2024 marketing year. Their corresponding wheat production was 91.5 million and 23 million metric tons, respectively [23]. According to the Federal State Statistics Service [24], the Kursk region ranks seventh in Russia, considering agricultural production. Figure 3 demonstrates the averaged map of specific activities of cesium isotopes in wheat after the severe accident and the large atmospheric radionuclide release (deposition **after harvesting**). Assuming the maximum permitted level of cesium contamination of 1250 Bq·kg^{-1} [25], the simulated specific activities of cesium isotopes in wheat ≥ 1250 Bq·kg^{-1} can be observed at distances up to 15 km from KuNPP. These specific activities are related to ripe wheat, representing a one-year delay after the deposition. However, in the case of simulated specific activities in wheat **before harvesting** (at the beginning of August 2024), such activities (≥ 1250 Bq·kg^{-1}) were found at distances of up to several hundreds of km from KuNPP, attributable to the direct deposition on already matured plants. As a result, wheat and other agricultural commodities from these areas may be subject to restrictions on distribution and consumption, and will require control measures, even for areas of Ukraine. The severe accident at KuNPP can therefore significantly reduce the crop production in both regions.

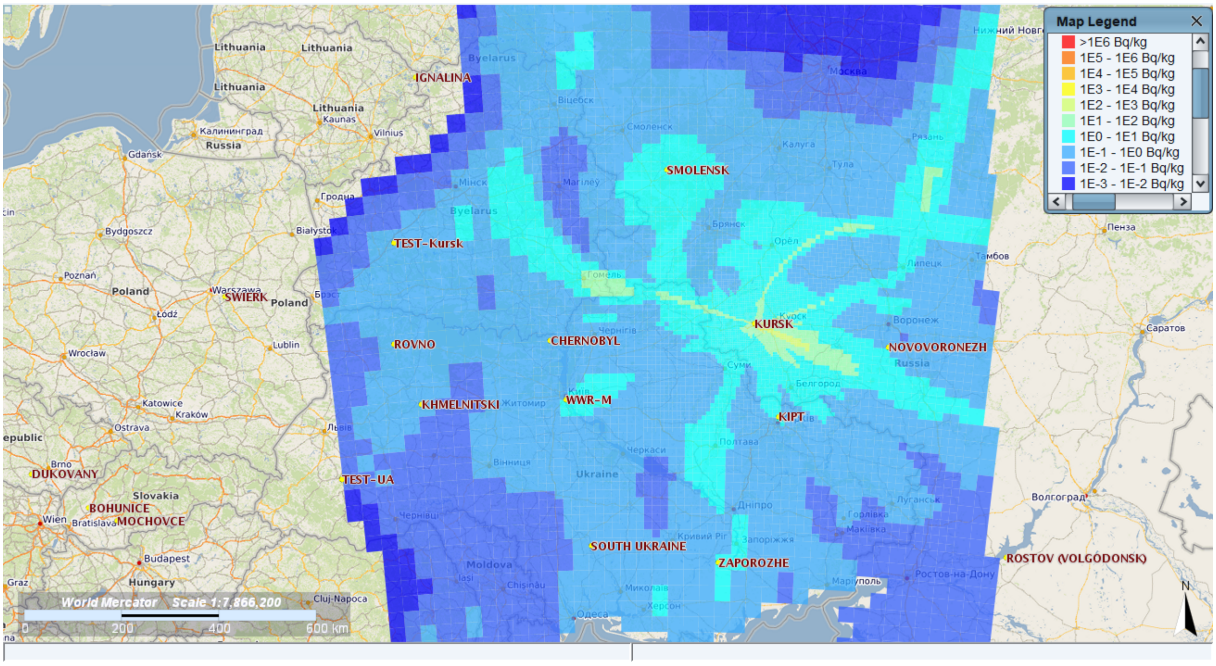

Figure 3. Map of specific activities of cesium isotopes in wheat (deposition after harvesting)

4 CONCLUSION

The actual situation at KuNPP has being followed with a rising interest from the European community. In the study, calculations of the postulated event at KuNPP were conducted, starting from the initial estimation of the mass inventory to the potential radiological consequences. According to the results of the simulations, the Russian and Ukrainian border territories will be the most affected (up to several hundreds of km) after the severe accident at KuNPP and will require protective measures for inhabitants. Moreover, agricultural fields near the NPP will be potentially affected, while the produced crops, e.g. wheat, may come under the export and consumption restrictions. The future work will continue in the source term spread prediction and the methodology improvements, according to domestic and international collaborations.

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