Zeszyty Naukowe SGSP 2023, No. 87

CBRN THREATS TO UKRAINE DURING THE RUSSIAN AGGRESSION: MITIGATING GAMMA RADIATION HAZARDS-INNOVATIVE COUNTERMEASURES AND DECONTAMINATION STRATEGIES IN THE CONTEXT OF POTENTIAL DESTRUCTION OF THE ZAPORIZHZHIA NUCLEAR POWER PLANT

Łukasz Szklarski[1]*
[1] ITTI Sp. zo.o.
* Coresspondence: lukasz.szklarski@itti.com.pl

Abstract

This paper investigates potential countermeasures to mitigate the disastrous effects of gamma radiation exposure in the event of a possible destruction of the Zaporizhzhia Nuclear Power Plant, Ukraine's largest nuclear facility, due to escalating conflicts. The potential destruction could result in an unparalleled release of gamma radiation, posing significant threats to human health and the environment. By examining the radiological dangers of gamma radiation, past case studies of radiation exposure, current countermeasures, as well as the limitations and challenges of these strategies, we may provide a comprehensive overview of the multidimensional nature of this potential crisis. The paper also explores innovative approaches in decontamination under resource constraints, focusing on dry decontamination, the use of alternative fluids, and the effective management of decontamination effluents.

Keywords: gamma radiation, nuclear disaster, civil protection, Zaporizhzhia Nuclear Power Plant, decontamination, radiation countermeasures, radiological dangers, dry decontamination, alternative fluids, decontamination effluents

1. Introduction

The ongoing geopolitical tensions and escalating conflicts in Ukraine create an alarming potential for nuclear disasters, particularly due to the possible destruction

---

DOI: 10.5604/01.3001.0053.9115
Received: 05.07.2023 Revised: 13.09.2023 Accepted: 13.09.2023

of the Zaporizhzhia Nuclear Power Plant, the largest of its kind in Ukraine and one of the biggest in Europe. This plant's destruction could lead to an extensive release of gamma radiation, presenting far-reaching and long-term impacts on human health, ecology and overall quality of life in affected regions.

Gamma radiation, a form of ionizing radiation, can cause serious damage to living cells, which could lead to cancers and other radiation-induced diseases (EPA, 2023). This issue becomes even more significant considering the absence of physical barriers that could completely block this high-energy radiation, necessitating robust countermeasures to protect the public and the environment.

Drawing lessons from past nuclear disasters, such as Chernobyl and Fukushima, we can discern the severe consequences of inadequate or delayed responses. However, the practical application of existing countermeasures presents numerous challenges, especially in situations where resources, particularly water, are scarce.

This paper provides a comprehensive overview of the dangers posed by gamma radiation and discusses the possible countermeasures that could be deployed to mitigate these risks. It further explores the innovative approaches that could be used for decontamination in situations of low resource availability, thereby contributing to the body of knowledge in radiation disaster management.

2. Methodology

In this article, the general research question posed is: “What are the current radiological threats facing Ukraine, and what possible countermeasures exist?” The research approach used to explore this question has been formed by two significant components: the author's 15 years of experience in the security domain, specifically in Chemical, Biological, Radiological, Nuclear (CBRN) defence, and a meticulous selection of relevant scientific papers authored by recognized experts and institutions in the field of radiological protection.

The author's experience in CBRN defence provides a unique and practical perspective on the topic, as it is enriched by insights gathered during the execution of numerous research projects within the CBRN domain for the European Union and the European Defense Agency (EDA). This practical understanding is of particular importance, as the author has also acted as a coordinator of two significant research projects for the European Commission (EC): EU-RADION and EU-SENSE. These projects have contributed significantly to the European body of knowledge on radiological threats and their countermeasures.

What is more, the author undertook an extensive review of scientific literature, selecting key papers from pertinent authors and institutions known for their contribution to the field of radiological protection. This selection of academic sources offers a theoretical backbone to the article and ensures the incorporation of the most recent and relevant research findings.

Each of the subsequent sections of the article addresses a specific subsidiary research question, leading to a comprehensive understanding of the main research question:

1) **Radiological Dangers of Gamma Radiation:** "What are the biological and environmental effects of gamma radiation?"
2) **Possible Contamination during Nuclear Power Plant Explosion or Bombing:** "What types of contamination can occur during a nuclear power plant disaster, and how does the contamination propagate?"
3) **Potential Threats for Ukraine in Case of Zaporizhzhia Nuclear Power Plant Explosion:** "What are the immediate and long-term threats to Ukraine in the event of a disaster at the Zaporizhzhia Nuclear Power Plant?"
4) **Potential Threats for Poland in Case of Zaporizhzhia Nuclear Power Plant Explosion:** "What are the potential threats to Poland in the event of a disaster at the Zaporizhzhia Nuclear Power Plant?"
5) **Current Countermeasures against Gamma Radiation:** "What countermeasures are currently available against gamma radiation and what are their advantages and limitations?"
6) **Case Studies of Gamma Radiation Exposure:** "What can past incidents of gamma radiation exposure teach us about its real-world effects and how to better prepare for and manage such events?"
7) **Challenges and Limitations of Current Countermeasures:** "What challenges and limitations are associated with current gamma radiation countermeasures?"
8) **How to Protect Ukrainian Population in Case of Explosion or Contamination from Zaporizhzhia Nuclear Power Plant:** "What strategies can be implemented to protect the Ukrainian population in the event of a disaster at the Zaporizhzhia Nuclear Power Plant?"
9) **How to Ensure Decontamination in Low Availability Resources, Especially Low Water Availability:** "How can effective decontamination be achieved in situations with limited resources, particularly limited water availability?"
10) **Decontamination Methods (Dry Decontamination, Low-Water Decontamination, Alternative Fluids, Decontamination of Humans, Recovery and Recycling of Decontamination Effluents):** "What are the various decontamination methods that can be employed in resource-constrained scenarios, and how can human decontamination and the management of decontamination effluents be managed?"

3. Results

3.1. Radiological Dangers of Gamma Radiation

Gamma radiation, occupying the highest energy position in the electromagnetic spectrum, is a formidable challenge in radiation protection. The significant energy it carries allows it to easily penetrate most types of matter, including human tissue, rendering ordinary shielding methods largely ineffective (Cember, & Johnson, 2008). As a result, it is capable of causing extensive cellular damage that leads to a variety of health issues.

Unlike Alpha or Beta radiation, which can be blocked by a sheet of paper or aluminium respectively, Gamma radiation requires dense, heavy materials for shielding, such as lead or concrete. The thick shielding is needed to absorb or scatter the gamma rays and prevent them from reaching the human body (Nuclear Regulatory Commission 2023).

When gamma radiation interacts with human tissue, it can ionize atoms within cells, resulting in the generation of charged particles and free radicals. These particles and radicals can then interact with biological macromolecules, like DNA, proteins and lipids, leading to their damage or dysfunction (Valko, Rhodes Moncol, Izakovic, & Mazur, 2006). This can cause a multitude of biological effects, ranging from minor cellular damage to substantial harm leading to cell death.

The extent of damage in living tissue is primarily determined by the absorbed dose of gamma radiation. At lower doses, the body might successfully repair the DNA and other cellular damage. However, exposure to higher doses can lead to acute radiation syndrome, a severe illness that can cause symptoms such as nausea, vomiting, diarrhoea, and in more extreme cases, neurological issues and death (Hall, & Giaccia, 2012).

Chronic exposure to lower levels of gamma radiation can also cause significant health issues. The damage to DNA can lead to mutations, some of which might trigger the development of various types of cancer. These effects may not be immediately apparent and may appear many years after the initial exposure (Cardis, Vrijheid, Blettner, Gilbert, Hakama, Hill, Tirmarche, 2007).

A profound understanding of the biological effects of gamma radiation is crucial for the development of countermeasures and strategies aimed at minimizing exposure and managing the consequences of a nuclear disaster.

3.2. Potential Contamination during a Nuclear Power Plant Explosion or Bombing

A nuclear power plant explosion or nuclear bombing poses serious contamination threats, with gamma radiation being one of the most dangerous aspects. When a nuclear power plant experiences a catastrophic event such as the meltdowns witnessed in Chernobyl or Fukushima, a significant amount of radioactive materials can be released into the environment (Steinhauser, Brandl, & Johnson, 2014). In addition to radioactive isotopes like iodine-131 or cesium-137, the dispersion of gamma radiation, which travels at the speed of light, can cause immediate and long-lasting damage (Hosoda, Tokonami, Sorimachi, Monzen, Osanai, Yamada, Nakata, 2011).

Gamma radiation exposure following a nuclear incident can occur in two main ways. The first is through initial radiation, which occurs at the time of the explosion and can extend over a large area. This initial radiation can cause immediate health effects, including acute radiation syndrome. The second form of exposure is through residual radiation, primarily from the fallout. Fallout refers to the radioactive particles that are carried into the upper atmosphere following a nuclear explosion and that subsequently fall back to earth, contaminating large areas (Glasstone, & Dolan, 1977).

Furthermore, nuclear bombings, similarly as the ones in Hiroshima and Nagasaki, demonstrate the destructive power of nuclear weapons, which release a tremendous amount of energy in the form of blast, heat and radiation, including gamma radiation (Oughterson & Warren, 1956). Gamma radiation from a nuclear explosion can cause both immediate and delayed effects. Immediate effects include severe burns and radiation sickness, while delayed effects can include various types of cancer and genetic damage.

For these reasons, understanding the risks of contamination from gamma radiation in the event of a nuclear power plant explosion or bombing is crucial for disaster preparedness and response.

3.3. Potential Threats for Ukraine in Case of Zaporizhzhia Nuclear Power Plant Explosion

Zaporizhzhia Nuclear Power Plant, located in Enerhodar, Ukraine, is the largest nuclear power plant in Europe and among the top ten globally in terms of capacity (Wikipedia, 2023). A potential explosion at this facility would have significant implications not only for Ukraine but also for Europe at large, given its sheer size and proximity to other European nations.

In the immediate vicinity of the explosion, a surge of gamma radiation would pose a severe threat to plant workers and local residents. Depending on the scale of the explosion and subsequent containment efforts, this could lead to acute radiation syndrome, along with other immediate health effects (Hall, & Giaccia, 2012). Moreover, widespread contamination of the local environment would likely occur, including the potential contamination of the Kakhovka Reservoir on the Dnieper River, which could disrupt water supply for a large part of Ukraine (Ratnaweera, Pivovarov, 2019)

Furthermore, the release into the atmosphere of radioactive material, including gamma-emitting isotopes, would lead to the contamination of a wider area. Wind patterns and weather conditions would play a significant role in determining the spread of this radioactive fallout. Depending on these factors, major cities like Dnipro, Donetsk and even Kyiv could be affected (Foreign Broadcast Information Service, 1995).

Long-term health effects are another serious concern. As observed in the aftermath of Chernobyl, exposure to gamma radiation and other radioactive materials could increase the incidence of cancers, particularly thyroid cancer due to the release of iodine-131, as well as other radiation-induced diseases in the affected populations (Burlakova, Naidich, 2006).

In addition, an explosion at Zaporizhzhia would have severe socio-economic implications. Mass evacuations, loss of electricity, agricultural damage and the long-term costs of decontamination efforts and health care for those affected would have a significant impact on Ukraine's economy.

Therefore, it is crucial to have robust and effective countermeasures in place to minimize the impact of such a disaster and to protect the health of those in affected areas.

3.4. Potential Threats for Poland in Case of Zaporizhzhia Nuclear Power Plant Explosion

Poland, located to the northwest of Ukraine, would not be immune to the fallout of a catastrophic event at the Zaporizhzhia Nuclear Power Plant. Although the country does not share a border with the Zaporizhzhia region, the dispersion of radioactive materials following a nuclear disaster can be widespread, carried by wind and weather patterns, affecting regions far beyond the immediate vicinity of the explosion (Povinec, Hirose, Aoyama, Tateda, 2021).

Gamma radiation, due to its penetrating nature, would pose a significant risk during the initial phase of a nuclear disaster. However, Poland's geographical distance from Zaporizhzhia would largely protect it from this immediate release of gamma radiation.

The more significant threat to Poland would likely come from the fallout of radioactive materials, including gamma-emitting isotopes such as cesium-137, which could be carried by prevailing winds over large distances. The level of contamination in Poland would be determined by several factors, including the scale of the explosion, the height at which radioactive materials are released into the atmosphere, weather conditions and the effectiveness of emergency responses (IAEA, 2006).

Upon reaching Poland, these radioactive materials could contaminate large areas of land, impacting agriculture and potentially entering the food chain, similarly to what occurred following the Chernobyl disaster in 1986 (Kashparov et al., 2003). Long-term exposure to those radioactive materials can increase the risk of various cancers and other health conditions (Cardis et al., 2007).

Aside from the direct health impact, a nuclear incident at the Zaporizhzhia plant could have significant socio-economic consequences for Poland. Potential contamination could disrupt trade, particularly in agricultural products, and lead to increased costs related to health care and possible decontamination efforts.

It is important to note that while the potential threats are significant, they are also contingent on a wide range of factors. Therefore, maintaining and improving nuclear safety measures, as well as having robust emergency preparedness and response plans in place, are critical for Poland and all European nations.

3.5. Current Countermeasures against Gamma Radiation

The potentially catastrophic effects of gamma radiation exposure have led to the development of various countermeasures. These countermeasures aim to prevent or reduce exposure, shield individuals and structures from radiation, and manage the health effects post-exposure (Chodick et al., 2008).

The first line of defence against gamma radiation exposure is to prevent or limit direct exposure. This is achieved through appropriate safety protocols and regulations in environments where gamma radiation is present, such as nuclear power plants. Protective clothing and equipment can provide some shielding from gamma radiation, but their effectiveness is limited due to the high penetrating power of gamma radiation (Eckerman & Endo 2009).

Structural shielding is a more effective countermeasure, with buildings and other structures designed to reduce the penetration of gamma radiation. Materials that are dense and have a high atomic number, such as lead and concrete, are commonly used for shielding (Kathren, 1996).

In the case of a nuclear disaster, countermeasures include evacuation, sheltering in place and the use of stable iodine prophylaxis. Evacuation can prevent exposure by moving people out of areas with high radiation levels. Sheltering in place, ideally in a structure with good radiation shielding, can protect against the initial fallout of a nuclear explosion. Stable iodine prophylaxis involves taking potassium iodide tablets to prevent the thyroid from absorbing radioactive iodine, thereby reducing the risk of thyroid cancer (WHO, 2011).

Following exposure, treatment options include the removal of contaminated clothing and washing of the skin to remove radioactive particles, as well as the administration of Prussian blue or Diethylenetriaminepentaacetic acid (DTPA) to enhance the elimination of certain radioactive isotopes from the body (Wojcik, 2002).

Despite these countermeasures, the high-energy nature of gamma radiation and its ability to travel great distances and penetrate matter, including the human body, pose significant challenges. Hence, ongoing research and development are necessary to improve existing countermeasures and develop new strategies for protection against gamma radiation.

3.6. Case Studies of Gamma Radiation Exposure

Historical instances of gamma radiation exposure provide valuable insights into the acute and long-term effects of radiation and the effectiveness of countermeasures. The following case studies represent significant events in which gamma radiation exposure played a crucial role.

- **The Hiroshima and Nagasaki Atomic Bombings (1945)**: These bombings in Japan during World War II represent the first large-scale exposure of a civilian population to gamma radiation (Otake, & Schull, 1998). Severe effects included burns, acute radiation syndrome and death. Long-term effects, such as increased incidences of cancers and other radiation-associated diseases, have been tracked by the Radiation Effects Research Foundation, providing valuable data on the health effects of gamma radiation exposure (Grant et al., 2017).
- **The Chernobyl Nuclear Disaster (1986)**: The explosion at the Chernobyl Nuclear Power Plant in Ukraine resulted in the release of large amounts of radioactive materials, including gamma-emitting isotopes (Medvedev, 1990). The acute radiation syndrome affected workers and first responders, while the long-term effects included increased rates of thyroid cancer, most likely due to exposure to radioactive iodine (Cardis et al., 2005). This event highlighted the importance of evacuation, decontamination and long-term monitoring and healthcare for affected populations.
- **The Goiânia Incident (1987)**: In this event in Brazil, a forgotten radiotherapy source containing cesium-137, a gamma-emitting isotope, was accidentally discovered and subsequently caused four deaths and significant contamination. This case highlighted the dangers of insufficient controls on radiation sources and the importance of public education on radiation safety (International Atomic Energy Agency, 1988).
- **The Fukushima Daiichi Nuclear Disaster (2011)**: The earthquake and tsunami in Japan led to meltdowns and the release of radioactive materials at the Fukushima Daiichi Nuclear Power Plant. Although the release of radioactive materials was smaller than that of Chernobyl, the disaster led to the evacuation of thousands of residents and underscored the importance of emergency preparedness and response measures in nuclear facilities (Steinhauser, Brandl & Johnson, 2014).

These case studies demonstrate the potential dangers of gamma radiation exposure and the importance of robust safety measures, emergency preparedness and response plans, as well as long-term care and monitoring of affected populations.

3.7. Challenges and Limitations of Current Countermeasures

While we have made substantial strides in the development of countermeasures against gamma radiation, these interventions are not without limitations and face numerous challenges.

- **Effectiveness of shielding materials**: Gamma radiation, due to its high energy and penetrating power, requires dense and heavy materials, such as lead or concrete, for effective shielding. The need for these materials can make practical implementation challenging, particularly in public protection scenarios where rapid deployment is needed (Zeeb, & Shannoun, 2009).
- **Availability and distribution of radiation sickness treatments**: Potassium iodide tablets can prevent the absorption of radioactive iodine by the thyroid, reducing the risk of thyroid cancer. However, the availability and timely distribution of these tablets during a nuclear emergency can be a logistical challenge (Becker, 2004).
- **Predicting radiation exposure**: Accurate prediction of the extent and pattern of gamma radiation exposure following a nuclear incident is complex due to variables such as weather conditions, the nature of the incident, and the characteristics of the surrounding environment (Hofman, Monte, 2011).
- **Long-term effects**: Many of the health effects of gamma radiation exposure, such as cancer, may take years or even decades to become apparent. This makes monitoring and providing long-term care for exposed populations challenging (McFee, Leikin, 2003).
- **Public understanding and cooperation**: Effective countermeasures often rely on public understanding and cooperation. However, misconceptions and fear of radiation can interfere with the implementation of protective measures (Becker, 2007).

Given these challenges, continued research and development of countermeasures, as well as public education on radiation safety and the appropriate responses to a nuclear incident, are essential for minimizing the harm caused by gamma radiation.

3.8. Protection of Ukrainian Population in Case of Zaporizhzhia Nuclear Power Plant Explosion or Contamination

In the event of an explosion or contamination from the Zaporizhzhia Nuclear Power Plant, the protection of the Ukrainian population would involve several steps aimed at mitigating both immediate and long-term risks. The following measures should be considered:

- **Evacuation and Sheltering**: Immediate evacuation of residents within the potential contamination zone is essential (Wheatley, Sovacool, Sornette, 2017). This would require clear, effective communication from government and emergency response officials. For those outside the immediate danger zone but still at risk of exposure, the instruction may be to stay indoors and seal homes to prevent radioactive particles from entering (Rubin, Amlôt, Page, Wessely, 2010).

- **Radiation Sickness Treatments**: The distribution of potassium iodide tablets to those at risk of exposure could help reduce the risk of thyroid cancer, a common long-term effect of radiation exposure (Wiwanitkit, 2011). Ensuring a sufficient stockpile of these tablets and a strategy for quick distribution is crucial.
- **Contamination Control**: Decontamination efforts would involve removing radioactive particles from individuals and environments (Devell, Guntay, Powers, 1995). This may include the use of radiation detection devices to identify contaminated individuals and the establishment of decontamination stations.
- **Long-term Monitoring and Healthcare**: Given that the health effects of radiation exposure may take years to become apparent, long-term healthcare and monitoring of the exposed population would be necessary. This could involve regular health check-ups and the provision of mental health services to address the psychological impact of the disaster (Havenaar et al., 1997).
- **Public Education**: Educating the public about radiation safety and the correct responses to a nuclear incident can enhance the effectiveness of these measures. This could involve the distribution of information materials, training sessions and regular drills to ensure that the public is prepared for this type of an event (Havenaar, Rumyantzeva, 2006).

These measures, while not exhaustive, would form a critical part of response to a potential explosion or contamination event at the Zaporizhzhia Nuclear Power Plant.

3.9. Ensuring Decontamination in Low Resource Settings, Particularly with Low Water Availability

In settings where resources, particularly water, are scarce, ensuring decontamination following a nuclear incident can be challenging. However, there are methods that can be employed to optimize available resources and increase the efficacy of decontamination procedures:

- **Prioritizing Decontamination**: Not all contaminated objects or areas will pose the same risk. Identifying the most highly contaminated areas and those with the strongest likelihood of human contact should be prioritized for decontamination (Raskob, Landman, 2010).
- **Dry Decontamination Methods**: If water is scarce, dry decontamination methods may be employed. For instance, absorbent materials such

as zeolite minerals or bentonite clay can be used to bind and remove radioactive particles from surfaces (Bandosz, 2012). Another option could be vacuuming, which can remove particulate contamination.
- **Low-Water Decontamination**: If some water is available, it can be used sparingly in conjunction with detergents to increase its efficacy. Small amounts of water with a high concentration of detergent can be used to wash down surfaces, followed by a clean water rinse (Rintamaa, Aho-Mantila, 2011).
- **Alternative Fluids**: In some cases, other fluids such as oils can be used to remove contamination. This can be particularly effective for decontaminating machinery or vehicles (Kovacs, 2006)
- **Decontamination of Humans**: In the case of human decontamination, dry methods such as brushing or the use of absorbent materials can be applied, followed by a thorough but water-efficient wash with soap and water if available (Severa, Bár, 1991).
- **Recovery and Recycling of Decontamination Effluents**: Developing a system to treat and reuse effluents from the decontamination process can further economize the water usage and ensure safety (Kadadou, Said 2023).

The key to managing decontamination in resource-limited settings is planning and preparedness. Having a clear plan in place that takes into account resource limitations and includes alternative decontamination methods can help ensure effective response should a nuclear incident occur.

3.9.1. Expanded Discussion on Dry Decontamination Methods

In situations where water is in limited supply or completely unavailable, dry decontamination methods offer an effective alternative for reducing radiation exposure. Here are some further details on these methods:
- **Absorbent Materials**: As previously mentioned, absorbent materials such as zeolite minerals and bentonite clay have been used with success for dry decontamination. Zeolite, a microporous mineral, is particularly effective because of its large surface area and its ion-exchange properties, which allow it to selectively absorb certain ions—in this case, radioactive ions (Bish, DMing, 2018). Similarly, bentonite clay can absorb radioactive ions and retain them in its layered structure, preventing them from being released back into the environment (Bhattacharyya, Gupta, 2008).
- **Vacuuming**: This method is particularly effective for removing loose contamination from surfaces. High-efficiency particulate air (HEPA) filtered vacuums can remove particulates without re-releasing them into the environment (U.S. Department of Energy, 2002). This method is most effective when the contaminated material is dry and particulate in nature.
- **Brushing and Wiping**: Dry brushing can dislodge radioactive particles, especially from rough surfaces. Similarly, wiping with dry cloths or

specialized wipes can help remove contamination (National Council on Radiation Protection and Measurements, 2005). These methods are labour-intensive yet quite effective, particularly for smaller items or areas.

- **Abrasive Methods**: For tougher contaminants, abrasive methods such as sandblasting or grinding might prove to be effective. These methods physically remove a layer of material from the contaminated surface, taking the radioactive particles with it (Sicilia, Aparicio, González, 2022). However, they also generate dust, which must be properly managed to prevent the spread of contamination.
- **Strippable Coatings**: In some cases, a strippable coating can be applied to a contaminated surface. When the coating dries, it can be peeled off, taking the radioactive particles with it (KArchibald, Demmer, Argyle, 1999). These coatings are particularly useful for decontaminating complex shapes and surfaces that would be difficult to clean with other methods.

Each of these dry decontamination methods has its strengths and weaknesses, and the most effective method will depend on the specifics of the contamination event. However, they all can all be effective tools in the battle intended to minimize radiation exposure in the wake of a nuclear disaster.

3.9.2. Expanded Discussion on Low-Water Decontamination

In situations where water is scarce but not entirely unavailable, low-water decontamination methods can be used to effectively reduce radiation exposure. These methods make the best use of the limited water available and often involve adding specific compounds to enhance the efficiency of decontamination. Some strategies include:

- **Concentrated Detergents**: A small amount of water can be used more efficiently by adding detergents. The surfactants in detergents reduce surface tension, allowing the water to spread and penetrate more effectively, making it more capable of removing contamination (Kohli, 2013). This method often involves applying a concentrated detergent solution to the contaminated area, letting it sit to dissolve the contamination, and then wiping or rinsing it away with clean water.
- **Wipe Sampling**: This is a standard method used for detecting surface contamination. It involves wiping a small, predetermined area with a damp cloth or paper and then analysing the wipe for radioactivity. The same process can be adapted for decontamination purposes, particularly for small, non-porous surfaces (International Atomic Energy Agency, 2003).
- **Spray-and-Wipe Method**: This is an extension of the wipe sampling method, where a small amount of water or detergent solution is sprayed onto the contaminated surface and then wiped off. This is particularly effective for larger surfaces or surfaces with intricate parts, where complete immersion is impractical (Gregor, Chockie, 2006).

- **Spot Cleaning**: Rather than attempting to decontaminate an entire area, focus can be given to spots of highest contamination. A handheld radiation detector can be used to locate these spots, and a small amount of water or detergent solution can be used to clean them. This method is particularly effective in reducing overall radiation levels when resources are scarce (National Council on Radiation Protection and Measurements, 2010).

The aim of these low-water decontamination methods is to maximize the efficiency of available water resources, while ensuring that as much radioactive material as possible is removed from the environment.

3.9.3. Expanded Discussion on Alternative Fluids

When the water supply is limited or not ideal for decontamination efforts, alternative fluids can be employed. These fluids may have such properties as high solubility for specific radioactive compounds or the ability to chemically react with and neutralize radioactive materials. Here are some key examples:

- **Chelating Agents**: Chelating agents are substances that can bind and form multiple bonds with a single metal ion, and they were found to be particularly effective in dissolving radioactive metals. Examples of these agents include ethylenediaminetetraacetic acid (EDTA) and diethylenetriaminepentaacetic acid (DTPA). These agents can be dissolved in a minimal amount of water and used to effectively decontaminate surfaces (International Atomic Energy Agency, 2006).
- **Acids and Bases**: Depending on the nature of the contamination, certain acids or bases can be effective at dissolving radioactive compounds. Citric acid, for instance, is often used to decontaminate metal surfaces (International Atomic Energy Agency, 1998). Conversely, bases such as sodium hydroxide can be used to dissolve and neutralize acidic radioactive waste (Bonnesen, Moyer, Presley, 1996).
- **Organic Solvents**: Organic solvents like ethanol or acetone can be used to dissolve organic radioactive compounds. These solvents can be particularly effective when dealing with contamination that is not water-soluble (Liu, He, Xie, Ge, 2022).
- **Complexing Agents**: Some agents, like citric acid and oxalic acid, can react with radioactive ions to form a complex, effectively encapsulating the ion and rendering it less harmful. This method is especially useful when dealing with alpha and beta emitters, as these radioactive ions can be shielded by the complex (Asadi Amirabadi et al., 2013).
- **Supercritical Fluids**: Supercritical fluids are substances at a temperature and pressure above their critical point, where distinct liquid and gas phases do not exist. Supercritical carbon dioxide (scCO2) is an example of such a fluid. It has been used successfully for the decontamination of nuclear equipment,

as it is able to dissolve and carry away a wide variety of contaminants (Kim, Park, 2014).

These alternative fluids provide options for decontamination when water is scarce or when specific types of contamination present challenges to water-based decontamination methods.

3.9.4. Expanded Discussion on Decontamination of Humans

When individuals are exposed to radioactive materials, timely and effective decontamination is crucial to minimize health risks. Yet, the process must be undertaken with care to avoid further harm or discomfort. Here are some key methods:

- **Emergency Decontamination**: The initial step in human decontamination involves removing clothing to reduce the level of contamination. This step alone can eliminate up to 90% of external contamination (International Atomic Energy Agency, 2003). Washing with mild soap and water, without scrubbing or scratching the skin, is then recommended to remove contaminants. To clean the eyes, water or saline solution should be used (United States Environmental Protection Agency, 2006).
- **Chelation Therapy**: For internal contamination, chelation therapy is a standard treatment. It involves the use of chelating agents that can bind to radioactive materials in the body, facilitating their elimination. DTPA and Prussian blue are the most commonly used chelating agents (Koenig, Goans, Hatchett, Mettler, 2005).
- **GI Tract Decontamination**: Certain substances, such as activated charcoal or certain alginates, can be administered to absorb radioactive materials in the gastrointestinal tract, reducing their absorption into the body (Silvestri, 2012).
- **Wound Decontamination**: In the event of contaminated wounds, careful cleaning and debridement is required. In many cases a weak solution of a chelating agent may be used to rinse the wound. If necessary, surgical intervention may be required (International Atomic Energy Agency, 2020).
- **Long-term Monitoring and Care**: Following the initial decontamination, long-term monitoring is often required. This can include regular check-ups and continued therapy to manage long-term health effects, including potential cancer risks (Kamiya, Ozasa, Akiba, Niwa, 2015).

For all methods, the guiding principle is to reduce the dose as much as possible while ensuring the decontamination process itself causes no harm. All methods require trained healthcare professionals to ensure proper implementation.

3.9.5. Expanded Discussion on Recovery and Recycling of Decontamination Effluents

The recovery and recycling of decontamination effluents represent an important aspect of managing the aftermath of a nuclear event. By treating and reusing the materials used during decontamination, resources can be conserved, and the impact on the environment can be minimized. Here are some key points:

- **Volume Reduction**: The initial step in managing decontamination effluents is to reduce the volume of waste. This can be accomplished through methods such as evaporation, precipitation and filtration. Reduction of the waste volume not only makes subsequent steps more manageable but also limits the environmental footprint of the decontamination process (Rau, Alaimo, Ashbrook, Austin, Borenstein, 2000).
- **Radionuclide Removal**: Several techniques can be applied to remove radionuclides from decontamination effluents, including ion exchange, precipitation and sorption. Ion exchange resins are especially effective for removing caesium and strontium (Valecia 2012). Meanwhile, co-precipitation with ferric hydroxide can remove a variety of radionuclides, such as plutonium, americium and curium (Klochkova, Savel'ev, Yu, Pozdnyakova, 2019).
- **Recycling Decontamination Solutions**: In certain cases, decontamination solutions can be treated and reused. For instance, citric acid and oxalic acid solutions used for decontamination can be regenerated through a process involving evaporation, carbonation, and crystallization (Davydov et al., 2003).
- **Treatment of Secondary Wastes**: The management of secondary wastes, such as spent ion exchange resins and precipitates, is also crucial. These materials can be solidified or stabilized using cement or other binders before disposal (Faiz, Bouih, Fakhi, 2014).
- **Final Disposal**: Despite all efforts to recycle and reduce waste, some level of residual waste is unavoidable. This material must be safely disposed of in a way that isolates the radioactive material from the environment (Ojovan, 2011).

Efficient management of decontamination effluents not only helps protect the environment but also conserves valuable resources and facilitates a more sustainable approach to nuclear disaster response.

4. Conclusions

The potential destruction of the Zaporizhzhia Nuclear Power Plant, located in Ukraine, is a matter of critical concern for both local and international communities. A nuclear disaster at such a facility would pose serious threats due to the release of gamma radiation, a form of ionizing radiation that could lead to devastating health and environmental outcomes.

Our in-depth analysis of this issue highlighted the radiological dangers of gamma radiation, which underscores the importance of robust civil protection measures. It has become clear that previous incidents involving radiation exposure, such as Chernobyl or Fukushima, have left long-term implications on health and the environment, accentuating the importance of learning from these case studies.

The currently established countermeasures against gamma radiation exposure demonstrate certain effectiveness, but they also present clear challenges and limitations. The practicality of these measures under different circumstances, such as low resource or water availability, is a crucial aspect that necessitates innovative approaches, such as dry decontamination and the use of alternative fluids.

A focus on human decontamination revealed that a blend of immediate actions and long-term care are required to ensure the minimization of health risks. Meanwhile, the exploration of decontamination effluents management emphasized the need for sustainable practices that would facilitate recovery and recycling, reducing the environmental impact of the decontamination process.

In the context of a possible disaster at the Zaporizhzhia Nuclear Power Plant, this investigation underlines the imperative for a comprehensive, multidisciplinary approach. This approach should combine advanced knowledge in radiation science, medical treatment strategies, environmental management and community preparedness. Furthermore, continued research and the development of novel strategies will remain critical in enhancing our readiness to protect public health and environmental sustainability in the face of such potential nuclear incidents.

As the last part of conclusions the author formulates an answer for the general research question “What are the current radiological threats facing Ukraine, and what possible countermeasures exist?” Based on the exploration and analysis of the sections presented in this study, the response to this question is as follows:

“Ukraine, and specifically areas in proximity to the Zaporizhzhia Nuclear Power Plant, face significant radiological threats due to potential disasters such as explosions or other events that could lead to the release of radioactive substances. The immediate and long-term consequences of such an event could be severe, with high levels of gamma radiation posing substantial risks to human health, the environment and infrastructure. In the event of a nuclear disaster, such as an explosion at the Zaporizhzhia Nuclear Power Plant, the direct impacts could be catastrophic, especially for Ukraine. The degree of the disaster’s impact would depend on various factors, including the magnitude of the explosion, weather conditions, as well as the promptness and effectiveness of the response.

Given these severe threats, robust countermeasures are needed to prevent, mitigate and respond to potential radiological disasters. Current countermeasures against gamma radiation include physical protections (such as radiation-resistant materials and shelters), medical countermeasures (like potassium iodide to protect the thyroid gland) and technological solutions (such as radiation detection and monitoring systems). Each of these countermeasures has its advantages and limitations, and their effectiveness depends on factors such as resource availability, speed of deployment, and the specific context of the radiological threat.

However, these countermeasures can face significant challenges and limitations, particularly in resource-limited scenarios. Resource constraints connected with current military conflict could hamper decontamination efforts, especially when there is limited water availability. In such situations, alternative decontamination methods, such as dry decontamination and the use of alternative fluids, could prove to be valuable. Human decontamination and the management of decontamination effluents also pose considerable challenges that need to be addressed.

In conclusion, the current radiological threats facing Ukraine are severe, particularly due to the current military aggression from Russia. While various countermeasures against gamma radiation exist, their implementation can be challenging, especially in resource-limited situations. Therefore, continuous research, planning, and preparation are vital to enhance the effectiveness of these countermeasures and ensure the protection of the Ukrainian population against radiological threats".

Summary

This comprehensive study delves into the potential threats of gamma radiation exposure that could arise from the potential destruction of the Zaporizhzhia Nuclear Power Plant, Ukraine's largest nuclear facility. The paper provides an in-depth exploration of the radiological hazards associated with gamma radiation, illustrating these dangers with past case studies of radiation exposure. The effectiveness, challenges and limitations of existing countermeasures are critically evaluated, with a focus on their applicability in scenarios of resource and water scarcity.

To address these challenges, the paper proposes innovative approaches for decontamination under resource constraints. These include dry decontamination, the use of alternative fluids and the management of decontamination effluents. These strategies are analysed both for their potential application in protecting the human population and in minimizing the environmental impact.

The study concludes by stating that managing the risk of gamma radiation exposure from a potential nuclear disaster necessitates a multifaceted approach combining radiation science, medical treatment strategies, environmental management and community preparedness. This approach underlines the imperative for continued research and the development of novel strategies, which are essential for enhancing readiness and protecting public health and the environment in the face of such potential nuclear incidents. The paper serves as a valuable resource for stakeholders involved in civil protection and nuclear disaster management.

Funding

This research received no external funding.

References

1. *Gamma Radiation basics*, Environmental Protection Agency, https://www.epa.gov/radiation/radiation-basics.
2. Cember, H., & Johnson, T.E., (2008). *Introduction to Health Physics* (4th ed.). McGraw-Hill.
3. Hall, E. J., & Giaccia, A.J., (2012). *Radiobiology for the Radiologist* (7th ed.). Lippincott Williams & Wilkins.
4. *Radiation Shielding*, U.S. Nuclear Regulatory Commission, https://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics.html.
5. Valko, M., Rhodes, C.J., Moncol, J., Izakovic, M., & Mazur, M., (2006). Free radicals, metals and antioxidants in oxidative stress-induced cancer. *Chemico-Biological Interactions*, 160(1), 1–40.
6. Cardis, E., Vrijheid, M., Blettner, M., Gilbert, E., Hakama, M., Hill, C. et al., (2007). The 15-Country Collaborative Study of Cancer Risk among Radiation Workers in the Nuclear Industry: estimates of radiation-related cancer risks. *Radiation Research*, 167(4), 396–416.
7. Steinhauser, G., Brandl, A., & Johnson, T.E., (2014). Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts. *Science of the Total Environment*, 470, 800–817.
8. Hosoda, M., Tokonami, S., Sorimachi, A., Monzen, S., Osanai, M., Yamada, M. et al., (2011). The time variation of dose rate artificially increased by the Fukushima nuclear crisis. *Scientific Reports*, 1, 87.
9. Glasstone, S., & Dolan, P. J., (1977). *The Effects of Nuclear Weapons*. United States Department of Defense.
10. Oughterson, A.W., & Warren, S., (1956). *Medical effects of the atomic bomb in Japan*. McGraw-Hill.
11. Zaporizhzhia Nuclear Power Plant, https://en.wikipedia.org/wiki/Zaporizhzhia_Nuclear_Power_Plant.
12. Ratnaweera, H., Pivovarov, O.A., (eds.) (2019). *Physical and cyber safety in critical water infrastructure*. In: NATO Advanced Research Workshop on Physical and Cyber Safety in Critical Water Infrastructure, Amsterdam: IOS Press.
13. Daily Report: Central Eurasia, (1995). USA: The Service.
14. Burlakova, E.B., Naidich, V.I., (2006). *20 Years After the Chernobyl Accident: Past, Present and Future*. Hauppauge: Nova Publishers, 358.
15. Pavel P. Povinec, Katsumi Hirose, Michio Aoyama, Yutaka Tateda (2021) "Fukushima Accident: 10 Years After" Elsevier, 23 July 2021, 574.
16. IAEA, (2006). Environmental consequences of the Chernobyl accident and their remediation: Twenty years of experience. Vienna: International Atomic Energy Agency.
17. Kashparov, V.A., Lundin, S.M., Zvarych, S.I., Yoshchenko, V.I., Levchuk, S.E., Khomutinin, Y.V., Maloshtan, I.M., Protsak, V.P. (2003). Territory contamination with the radionuclides representing the fuel component of Chernobyl fallout. *Sci Total Environ.*, 317(1-3):105–19. DOI: 10.1016/S0048-9697(03)00336-X.

18. Cardis, E., Krewski, D., Boniol, M., Drozdovitch, V., Darby, S., Gilbert, E., . . . Vrijheid, M., (2006). Estimates of the cancer burden in Europe from radioactive fallout from the Chernobyl accident. *International Journal of Cancer*, 119(6), 1224–1235.
19. Cardis, E., Krewski, D., Boniol, M., Drozdovitch, V., Darby, S.C., Gilbert, E.S., Akiba, S., Benichou, J., Ferlay, J., Gandini, S., Hill, C., Howe, G., Kesminiene, A., Moser, M., Sanchez, M., Storm, H., Voisin, L., Boyle, P., (2008). Risk of cataract after exposure to low doses of ionizing radiation: a 20-year prospective cohort study among US radiologic technologists. *American Journal of Epidemiology*, 168(6), 620–631.
20. Eckerman, K.F., Endo, A., (2009). MIRD: Radionuclide Data and Decay Schemes. *Reston, VA: Society of Nuclear Medicine*, 2008.
21. Kathren, R.L., (1996). Pathway to a paradigm: the linear non-threshold dose-response model in historical context. The evolution of radiation protection philosophy. *Health Physics*, 70(3), 261–279.
22. World Health Organization, (2011). *Guidelines for iodine prophylaxis following nuclear accidents: update 1999*. World Health Organization.
23. Wojcik, A., (2002). The Medical Basis for Radiation-Accident Preparedness. The Clinical Care of Victims, Proceedings of the Fourth International REACT/TS Conference on the Medical Basis for Radiation-Accident Preparedness. *Radiation Research*, 158(1), 125.
24. Otake, M., Schull, W.J., (1998). Radiation-related brain damage and growth retardation among the prenatally exposed atomic bomb survivors. *International Journal of Radiation Biology*, 74(2), 159-171.
25. Grant, E.J., Brenner, A., Sugiyama, H., Sakata, R., Sadakane, A., Utada, M., Cahoon, E.K., Milder, C.M., Soda, M., Cullings, H.M., Preston, D.L., Mabuchi, K., Ozasa, K., (2017). Solid cancer incidence among the life span study of atomic bomb survivors: 1958–2009. *Radiation Research*, 187(5), 513–537.
26. Medvedev, Z., (1990). *The legacy of Chernobyl*. New York: Norton.
27. Cardis, E., Kesminiene, A., Ivanov, V., Malakhova, I., Shibata, Y., Khrouch, V., Drozdovitch, V., Maceika, E., Zvonova, I., Vlassov, O., Bouville A., Goulko, G., Hoshi, M., Abrosimov, A., Anoshko, J., Astakhova, L., Chekin, S., Demidchik, E., Galanti, R., Ito, M., Korobova, E., Lushnikov, E., Maksioutov, M., Masyakin, V., Nerovnia, A., Parshin, V., Parshkov, E., Piliptsevich, N., Pinchera, A., Polyakov, S., Shabeka, N, Suonio, E., Tenet, V., Tsyb, A., Yamashita, S., Williams, D., (2005). Risk of thyroid cancer after exposure to 131I in childhood. Journal of the National Cancer Institute, 97(10), 724–732.
28. International Atomic Energy Agency, (1988). *The radiological accident in Goiania*. IAEA.
29. Steinhauser, G., Brandl, A., Johnson, T.E., (2014). Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts. *Science of The Total Environment*, 470, 800–817.
30. Zeeb, H., & Shannoun, F., (eds.). (2009). *WHO handbook on indoor radon: a public health perspective*. World Health Organization.
31. Becker, S.M., (2004). Emergency communication and information issues in terrorist events involving radioactive materials. *Biosecurity and bioterrorism: biodefense strategy, practice, and science*, 2(3), 195–207.

32. Hofman, D., Monte. L., (2011). Computerised Decision Support Systems for the management of freshwater radioecological emergencies: assessment of the state-of-the-art with respect to the experiences and needs of end-users. *Journal of Environmental Radioactivity*, 102, 2, 119–127.
33. McFee, R.B., & Leikin, J.B., (2003). Death by polonium-210: lessons learned from the murder of former Soviet spy Alexander Litvinenko. *Clinical Toxicology*, 46(9), 819–822.
34. Becker, S.M. (2007). Communicating risk to the public following radiological incidents. *Journal of radiological protection*, 27(1), 17.
35. Wheatley, S., Sovacool, B., & Sornette, D., (2017). Of Disasters and Dragon Kings: A Statistical Analysis of Nuclear Power Incidents & Accidents. *Risk Analysis*, 37(1), 99–115.
36. Rubin, G.J., Amlôt, R., Page, L., & Wessely, S., (2010). Public perceptions, anxiety, and behaviour change in relation to the swine flu outbreak: cross sectional telephone survey. *BMJ*, 339, b2651.
37. Wiwanitkit V., (2011). Nuclear detonation, thyroid cancer and potassium iodide prophylaxis. *Indian journal of endocrinology and metabolism*, 15(2), 96–98.
38. Devell, L., Guntay, S., & Powers, D., (1995). *The Chernobyl reactor accident source term: development of a consensus view*. In: Proceedings of the CSNI specialist meeting on reactor accident source terms.
39. Havenaar, J.M., Rumyantzeva, G.M., Van den Brink, W., Poelijoe, N.W., van den Bout, J., van Engeland, H., & Koeter, M.W., (1997). Long-term mental health effects of the Chernobyl disaster: an epidemiologic survey in two former Soviet regions. *American Journal of Psychiatry*, 154(11), 1605–1607.
40. Havenaar, J.M., Rumyantzeva, G.M., (2006). *Long-Term Mental Health Effects of the Chernobyl Disaster: An Epidemiologic Survey in Two Former Soviet Regions*. https://doi.org/10.1176/ajp.154.11.1605.
41. Raskob, W., & Landman, C., (2010). The IMEKO TC8 Workshop on Metrological Infrastructure.
42. Bandosz, T.J., (2012). Activated Carbon Surfaces in Environmental Remediation. Elsevier.
43. Rintamaa, R., Aho-Mantila, I., (2011). *Plant life management and modernisation: Research challenges in the EU*. Nuclear Engineering and Design. 241, 9, 3389–3394.
44. Kovacs. P., (2006). Impacts of nuclear power plant life management and long-term operation. *NEA News*, 24, 2.
45. Severa, J., Bár, J., (1991). *Handbook of Radioactive Contamination and Decontamination*, Elsevier.
46. Kadadou, D., Said, E., (2023). Research advances in nuclear wastewater treatment using conventional and hybrid technologies: Towards sustainable wastewater reuse and recovery. *Journal of Water Process Engineering*, 2, 103604.
47. Bish, D., Ming, D., (2018). *Natural zeolites: occurrence, properties, applications*. Berlin: Walter de Gruyter GmbH & Co KG, 668.
48. Bhattacharyya, K.G., Gupta, S.S., (2008). Adsorption of a few heavy metals on natural and modified kaolinite and montmorillonite: a review. *Advances in colloid and interface science*, 140(2), 114–131.

49. U.S. Department of Energy, (2002). Radiological Control Manual. DOE M 440.1-1.
50. National Council on Radiation Protection and Measurements, (2005). Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism. NCRP Commentary No. 19.
51. I.Sicilia, S. Aparicio, M. González, (2022). *Radon Transport, Accumulation Patterns, and Mitigation Techniques Applied to Closed Spaces*. Atmosphere, 13(10), 1692.
52. K. Archibald, R. Demmer, M. Argyle (1999). *Cleaning and decontamination using strippable and protective coatings at the idaho national engineering and environmental laboratory*. WM'99 CONFERENCE, FEBRUARY 28–MARCH 4.
53. Kohli, R., (2013). *Developments in Surface Contamination and Cleaning Methods of Cleaning and Cleanliness Verification*, pp. 139–161.
54. International Atomic Energy Agency. (2003). Training in radiation protection and the safe use of radiation sources. *Safety reports series*, (20), 95–102.
55. Gregor, F., Chockie, A., (2006). *Aging Management and Life Extensionin the US Nuclear Power Industry*. Seattle: Chockie Group International.
56. National Council on Radiation Protection and Measurements, (2010). *Management of Persons Contaminated with Radionuclides: Handbook*. NCRP Report No. 161, Vol. II.
57. International Atomic Energy Agency, (2006). *Technologies for the remediation of radioactive contaminated sites. Radiation Safety Reports Series*, 40, 68–76.
58. International Atomic Energy Agency, (1998). New methods and techniques for decontamination in maintenance or decommissioning operations.
59. Bonnesen, V., Moyer, B.A., Presley, D.J., (1996). *Alkaline-Side Extraction of Technetium from Tank Waste Using Crown Ethers and Other Extractants*. DOI:10.2172/257317
60. Liu, S., He, Y., Xie, H., Ge, Y., (2022). *Technologies: Facing the Upcoming Wave of Decommissioning and Dismantling of Nuclear Facilities*. *Sustainability*, 14(7), 4021.
61. Amirabadi, E.A., Salimi, M., Ghal-Eh, N., Etaati, G.R., Asadi, H., (2013). Study of Neutron and Gamma Radiation Protective Shield. *International Journal of Innovation and Applied Studies*, 3, 1079–1085.
62. Kim, H., Park, K., (2014). *Decontamination of Heavy Metal in Soil by Using Supercritical Carbon Dioxide*. Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, May 29–30, 2014.
63. International Atomic Energy Agency. (2003). Medical management of radiological casualties. *Health Physics*, 85(1), 52–57.
64. United States Environmental Protection Agency. (2006). *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents*.
65. Koenig, K., Goans, R., Hatchett, R., Mettler, F., Jr, (2005). Medical treatment of radiological casualties: current concepts. *Ann Emerg Med.*, 2005. DOI: 10.1016/j.annemergmed.2005.01.020.
66. Silvestri, L., (2012). Selective decontamination of the digestive tract: an update of the evidence. *HSR Proc Intensive Care Cardiovasc Anesth.*, 2012; 4(1): 21–29.
67. International Atomic Energy Agency, (2020). *Medical Management of Radiation Injuries*. Safety Reports Series, No. 101.

68. Kamiya, K., Ozasa, K., Akiba, S., Niwa, O., (2015). Long-term effects of radiation exposure on health, *Lancet*, 386, 9992, 469–478.
69. Rau, E.H., Alaimo, R.J., Ashbrook, P.C., Austin, S.M., Borenstein, N., (2000). Minimization and management of wastes from biomedical research. *Environ Health Perspect.*, 108, 6.
70. Valecia, L., (2012). *Radioactive waste management in nuclear decommissioning projects*. Nuclear Decommissioning Planning, Execution and International Experience Woodhead Publishing Series in Energy, pp. 375–415.
71. Klochkova, N.V., Savel'ev, A.A., Pozdnyakova, N.Yu., (2019). Investigation of Americium Sorption from Model Liquid Radwaste Solutions Using TODGA-Based Solid-Phase Extractant. *Atomic Energy*, 127, 40–44.
72. Davydov, D., Davydov, Y., Toropov, I.G. et al., (2003). Development of a method for regeneration of spent electrochemical decontamination solution on the basis of data on speciation of metal ions in solution. *Czechoslovak Journal of Physics*, 53, A699–A704.
73. Faiz, Z., Bouih, A., Fakhi, S., (2014). Improvement of conditions for the radioactive ion exchange resinimmobilization in the cement Portland. *J. Mater. Environ. Sci.*, 6(1) (2015), 289–296.
74. Ojovan, M.I., (2011). Radioactive waste characterization and selection of processing technologies. Handbook of Advanced Radioactive Waste Conditioning Technologies Woodhead Publishing Series in Energy 2011, pp. 1–16.

ZAGROŻENIA CBRN NA UKRAINIE PODCZAS ROSYJSKIEJ AGRESJI: ŁAGODZENIE ZAGROŻEŃ ZWIĄZANYCH Z PROMIENIOWANIEM GAMMA – ŚRODKI ZARADCZE I STRATEGIE DEKONTAMINACJI W KONTEKŚCIE POTENCJALNEGO ZNISZCZENIA ELEKTROWNI JĄDROWEJ W ZAPOROŻU

Abstrakt

Niniejsza praca bada środki zaradcze mające na celu złagodzenie skutków ekspozycji na promieniowanie gamma w przypadku ewentualnego zniszczenia Elektrowni Jądrowej w Zaporożu, największej instalacji jądrowej na Ukrainie. Potencjalne zniszczenie mogłoby skutkować uwolnieniem promieniowania gamma, stanowiąc znaczące zagrożenie dla zdrowia ludzkiego i środowiska. Badając radiologiczne zagrożenia promieniowaniem gamma, przeszłe przypadki ekspozycji na promieniowanie, obecne środki zaradcze oraz ograniczenia i wyzwania związane z tymi strategiami, dostarczamy kompleksowy przegląd wielowymiarowej natury tego potencjalnego kryzysu. Praca analizuje również innowacyjne podejścia do dekontaminacji przy ograniczonych zasobach, koncentrując się na dekontaminacji suchej, użyciu alternatywnych płynów oraz efektywnym zarządzaniu zanieczyszczeniami powstałymi w wyniku dekontaminacji.

Słowa kluczowe: promieniowanie gamma, katastrofa jądrowa, ochrona ludności, Elektrownia Jądrowa w Zaporożu, dekontaminacja, środki zaradcze przeciwko radiacji, radiologiczne zagrożenia, sucha dekontaminacja, alternatywne płyny, zanieczyszczenia powstałe w wyniku dekontaminacji