RANKING OF NUCLEAR FACILITIES BY ASSESSING POTENTIAL RADIATION IMPACT ON THE ENVIRONMENT

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Abstract

The research presents a method for the evaluation and comparison of the impact of accidental releases from nuclear reactors and similar facilities on the environment. The radioecological risk was calculated, considering the probability of emergencies and their impact on the environment. The pine forest was employed as a reference ecosystem for assessment due to its high sensitivity as an indicator. A ranking of radioecological risk for various reactor facilities (VVER-1000, VVER-1200, PWR-890, BWR-1412, EPR-1600), was performed. The analysis revealed that the next-generation VVER-1200 reactor exhibits the lowest potential environmental impact.

1. INTRODUCTION

In the realm of advancing nuclear energy strategies, the top priority is to pioneer cutting-edge technologies and choose cost-effective solutions that are specifically tailored to the per-unit electricity generation cost [1]. This metric substantiates nuclear energy's competitiveness against alternatives. Simultaneously, ensuring the radiation and environmental safety of nuclear power plants during their construction is vital [2]. In shaping the future of the nuclear energy industry, comprehensive radioecological assessments are indispensable [3].

While normal nuclear plant operations adhere to safety regulations [4] and public exposure limits [5], potential risks persist in abnormal or emergency situations. The IAEA categorizes radiation emergencies separately, alongside planned and existing radiological situations [6].

This paper proposes a method to assess and compare nuclear reactor units and other facilities in regard to their potential environmental impact in case of accidental releases.

2. METHODOLOGICAL ASPECTS

2.1. Emergency Scenarios and Assessment Period

When planning nuclear power plants (NPPs) and other nuclear facilities, which have the potential to release radioactive materials, it is important to develop scenarios for both design basis (DBA) and beyond design basis accidents (BDBA). The set of scenarios can cover accidents of varying severity, including major accidents, according to international classifications. For example, Level 7 accidents on the INES scale have been described for Surry [7] and Peach Bottom [8] NPPs. Similar Level 7 accidents are considered for third-generation EPR reactor with a capacity of 1600 MW [9].

The study used data on hypothetical accidents at different types of nuclear power plants to determine their potential impact on the environment. Emergency scenarios developed for PWR-890 [7], BWR-1412 [8], EPR-1600 [9], VVER-1000 [10] and VVER-1200 [11] were considered. The key characteristics of the most severe emergency scenarios (total activity, release height and accident probability) are given in Table 1.

TABLE 1. KEY CHARACTERISTICS OF SEVERE EMERGENCY SCENARIOS

Reactor	Total activity, TBq	Release height, m	Probability, year^{-1}
PWR-890	$7{,}51 \cdot 10^{6}$	8,4	$1{,}0 \cdot 10^{-5} – 2{,}0 \cdot 10^{-5}$
BWR-1412	$2{,}38 \cdot 10^{7}$	39,6	$3{,}0 \cdot 10^{-7}$

Reactor	Total activity, TBq	Release height, m	Probability, year^{-1}
EPR-1600	$1{,}04 \cdot 10^8$	10	$3{,}83 \cdot 10^{-9}$
VVER-1200	$1{,}49 \cdot 10^4$	30	$1{,}0 \cdot 10^{-7}$
VVER-1000	$4{,}50 \cdot 10^5$	25	$1{,}0 \cdot 10^{-7}$

As a result of accidents, natural ecosystems experience acute radiation exposure in the initial period, followed by chronic irradiation. It is important to emphasize the significance of assessments for the immediate post-accident period, as acute radiation exposure can cause severe disturbances to natural communities. Not only do changes in the structure and functioning of ecosystems occur as a result of direct radiation effects, but they also arise from a combination of secondary post-radiation effects and recovery processes [12], [13].

2.2. Reference Natural Community

To assess acute radiation impact on biota, it is advisable to consider coniferous (pine) forests as the reference natural community because:

- pine tree is on the list of the ICRP's list of RAPs;
- pine canopies effectively capture a significant portion of radionuclides in atmosphere [10];
- the tree layer is preferable for use than mammals that move through radioactive areas;
- damage to the trees disrupts the ecosystem's overall structure and functioning;
- there is available data to parameterize migration-dosimetric models gathered from extensive studies in forest radioecology after the Kyshtym and Chernobyl accidents [12]-[21].

Studying a reference pine forest community with specific characteristics helps understand the migration of radionuclides in the "atmosphere - forest canopy - soil surface" system. Calculating the dose dynamics for conifers in the immediate aftermath of an accident is an effective method for assessing the acute radiation impact on the forest ecosystem [21].

2.3. Approach to Assessing Radioecological Accident Risk

Nuclear energy facilities can have environmental impacts. They can be characterized by two types of indicators: the probabilities of accidents (DBA and BDBA) and the effects of radioactive releases on the environment. The glossary of The IAEA glossary defines risk as follows [22]:

$$R = \sum_i p_i \cdot C_i$$

where p_i is the probability of occurrence of scenario or event sequence i and C_i is a measure of the consequence of that scenario or event sequence.

There are several indicators that can be used to measure the consequences of accidents (C), taking into account any uncertainties in their assessment. In the study [23], a comparison of radioecological accident indicators for three reactors of different types was conducted. Single severe accident scenarios were selected for each reactor without considering the probabilities of their realization. A radioecological ranking of scenarios was performed based on two methodological approaches:

- A "point" conservative assessment of the Radiation Impact Factor (RIF) [24] on the natural community - the tree layer of pine forest.
- Calculation of an indicator that takes into account the spatial distribution of fallout and, consequently, the variability of radiation doses to the trees.

Despite quantitative differences in the assessments, the qualitative results of the radioecological ranking of accident scenarios obtained by the two methods coincided [23]. Thus, for screening comparative assessments of nuclear energy facilities as potential sources of radiation impact on biota, a conservative approach can be employed. The RIF will be the characteristic used in this case to represent the consequences of an accident (C). It is determined by calculating the ratio between the maximum dose received by the reference natural community and the dose limit. The overall scheme of the approach for assessing radioecological accident risk for a reactor facility is shown in Fig. 1.

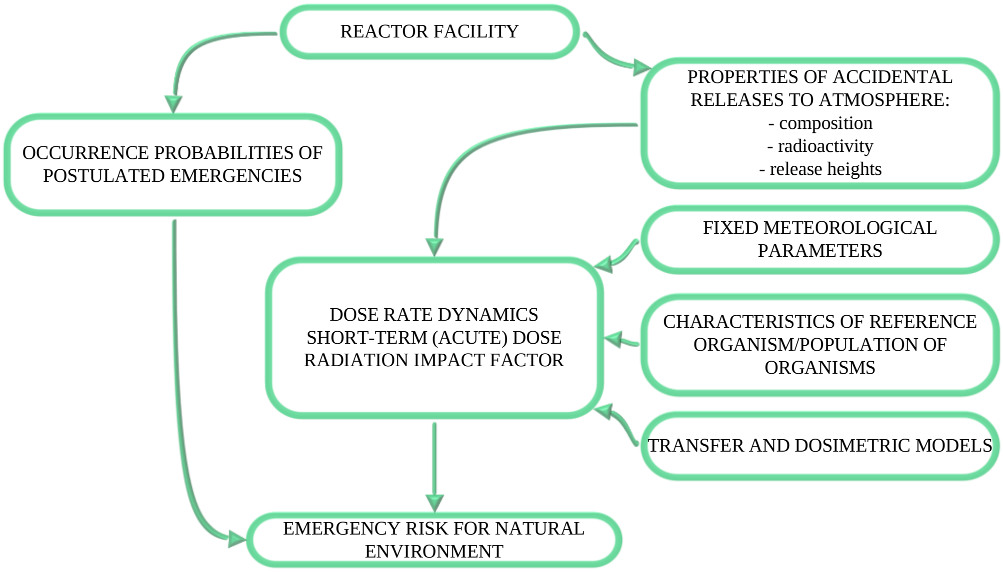

FIG. 1. Scheme for a conservative accident risk assessment of the impact of a reactor facility on the environment

2.4. Dose Criterion

To assess the Radiation Impact Factor, it is necessary to establish a dose limit for the reference natural object. It should be emphasized that the recommended Derived Reference Levels (DRLs) for the threshold dose rate of 1 mGy/day for chronic irradiation are not suitable for assessing the consequences of acute irradiation. This is due to a significant reduction in the dose rate during the first annual period after an accidental release [21]. Given that doses from severe accident scenarios can be fatal to pine trees, it is crucial to regard the lethal dose as the dose threshold. After thoroughly analyzing the data collected from experiments on the acute irradiation of pine forests [16] and the areas affected by Chernobyl fallout [17], [18], it has been determined that the accepted value for this indicator is 100 Gy.

2.5. Models and Parameters

Doses on pine trees were evaluated using a combination of migration and dosimetric models [21]. The transport of radionuclides in the atmosphere was calculated using a Gaussian model. Meteorological parameters included atmospheric stability category (F) and wind speed (0.5 m/s). Modelling radionuclide redistribution in the forest ecosystem considered primary retention by tree canopies (retention factor - 0.9), ecological decay (ecological decay constant - 7.7×10^{-3} day^{-1}), and radioactive decay.

The doses on the trees were calculated from two sources of ionizing radiation: radionuclides in the forest canopy (thick infinite source) and on the soil surface (thin infinite source) [23]. The model used in [23] assumed that the thickness of the layer known as "tree canopy" was 10 meters, and the density of the air-vegetation mixture was 2.4 kg/m^3. Besides doses from radionuclides distributed in the "trees - soil surface" system, there were also estimated doses of short-term irradiation of the trees from short-lived radionuclides in the radioactive plume according to the methodology mentioned in reference [25].

3. RADIOECOLOGICAL RANKING OF REACTOR FACILITIES

For all the emergency scenarios, radiation impact factors on the canopy of the pine forest were calculated using a conservative approach. The values of this indicator vary widely for each reactor (Fig. 2). For the PWR-890 reactor, the RIF ranges from 22 to 57, for BWR-1412 from 5 to 23, and for EPR-1600 from 0.001 to 8300. The wide range of variation happens because emergency scenarios have different characteristics. These include the composition of radioactive material, the radioactivity released into the air, and release height.

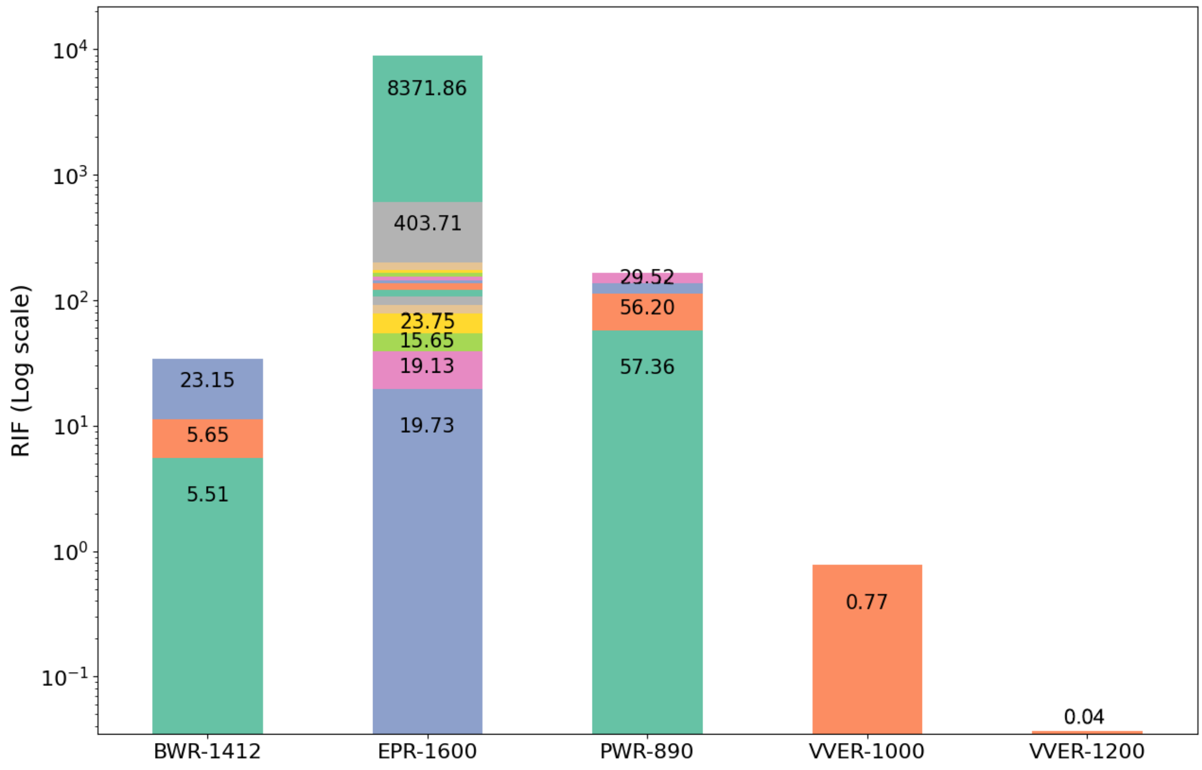

FIG. 2. Radiation impact factors for various reactors and scenarios

It is worth noting that for most of the scenarios of PWR-890, BWR-1412, and EPR-1600 reactors, the radiation impact index exceeds one. This means that the maximum dose on trees exceeds the established dose criterion (lethal dose). For VVER-1000 and VVER-1200, the RIF values are significantly less than 1. The minimum and maximum values of this indicator for VVER-1000 are 0.0005 and 0.77, and for VVER-1200, they are 0.0001 and 0.037, respectively.

The calculation results in [23] indicate that the comparative radioecological assessment of reactor installations, relying solely on one emergency scenario, is not comprehensive. To ensure a precise evaluation of the environmental radiation effects caused by various reactors, it is imperative to consider all conceivable combinations of hypothetical accidents. This is necessary because individual scenarios can vary significantly in their characteristics.

The results of the comparative accident radioecological risk evaluation for the reactors under consideration are depicted in Figure 3. According to the conservative risk assessment, the PWR-890 reactor is identified as potentially posing the greatest risk to biota. The calculations for this reactor employ the highest values within the range of accident scenario probabilities. Although the EPR-1600 reactor has the most severe scenario, its contribution to the overall risk value is minimized due to its low occurrence probability.

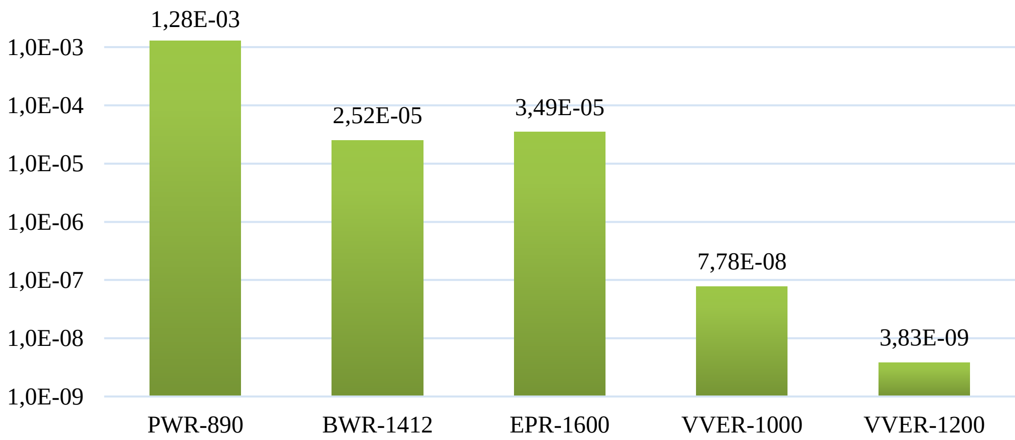

FIG. 3. Emergency risks of the impact of reactor facilities on the environment

The radioecological risks related to VVER-1000 and VVER-1200 reactors are low, mainly due to the relatively low levels of radionuclide activities in their compositions. Notably, the risk value for the advanced-generation VVER-1200 reactor is twenty times lower than that for the VVER-1000 reactor.

The probabilities of postulated accidents at VVER-1000 and VVER-1200 reactor installations (10^{-6} - 10^{-7} per year) are comparable to the values of similar indicators for PWR-890, BWR-1412, and two scenarios of the EPR-1600 reactor. The radioecological risks of VVER-1000 and VVER-1200 are low since the activities of radionuclides in their emergency scenarios are relatively low. Moreover, the R value for the next-generation VVER-1200 reactor is 20 times lower than the R value for the VVER-1000 reactor.

4. CONCLUSION

With the continuous progress of nuclear energy and the creation of innovative reactor facilities and fuel cycles, there is an urgent requirement for radioecological assessments. These assessments are essential in order to compare reactors and determine their potential impact on the environment. A proposed approach facilitates such a comparison by assessing radiation impact risks on a representative natural habitat – the canopy of pine forests.

Calculations have revealed that the risks to the environment vary greatly depending on the characteristics of the reactor facilities and emergency scenarios. According to the conducted assessments, the reactor VVER-1200, belonging to the "3+" generation, appears to be the safest for biota.

The approach to assess radioecological accident risks to the environment can be further developed by considering the distribution of doses over the radioactive area. The application of such a "spatial" approach has been demonstrated in a previous study for individual emergency scenarios.

Current methodology utilizes information on accident scenario attributes developed for reactor installations. This comprehensive strategy is not only applicable to assessing individual nuclear power plant units but also extends to other facets of the nuclear fuel cycle, thus serving as a comprehensive tool for gauging potential radiation hazards. Integrating such assessments during the preparatory phase of nuclear energy facilities and systems aligns with sustainability objectives and forms an integral part of their environmental validation.

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