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Source term dispersion analysis and construction of the probabilistic dispersion map around the Peach Bottom Unit-2 plant using the ASTEC and JRODOS codes☆

Onur Murat *, Fabrizio Gabrielli, Victor Hugo Sanchez-Espinoza

Karlsruhe Institute of Technology, Institute for Neutron Physics and Reactor Technology.Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany

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ABSTRACT

National regulatory authorities and Emergency Preparedness teams require accurate source term predictions to safeguard the public in the event of radiological emergencies, such as severe accidents at Nuclear Power Plants (NPPs). Consequently, reliable assessments of the radiological impacts of hypothetical Severe Accidents (SA) at NPPs are essential. In order to meet this need, a unique and robust platform of simulation codes has been developed at the Karlsruhe Institute of Technology (KIT) to assess the source term data and corresponding radiological consequences of severe accidents. This platform utilizes the CASMO5 code to calculate the fuel inventory in the reactor core and the European reference Accident Source Term Evaluation Code (ASTEC), developed by IRSN, to analyze the severe accident sequence, from initiation to the release of fission products into the environment. The source term data calculated by ASTEC is then used by the JRODOS code, developed by KIT, to assess the radiological effects of the dispersion. In this study, the described platform is used to evaluate the radiological consequences of a Station BlackOut (SBO) scenario at the Peach Bottom Unit-2 NPP. JRODOS analyses use representative dates to assess radiological impacts, as daily evaluations which are considers the possible each starting point computationally impractical. A methodology was developed to assess severe accident consequences for each grid around Peach Bottom Unit-2 NPP. This approach offers a detailed view of the accident's scope across the region, aiding in the development of appropriate plans for the early and intermediate phases of the accident. Thus, the proposed methodology provides valuable and detailed insights for evaluating emergency preparedness and response actions in the event of a SA at an NPP.

1. Introduction

Severe accident consequences bring significant risks to public health and the environment. Past experienced SAs, such as Chernobyl and Fukushima Daiichi, which led to large radiological releases into the environment, have highlighted the need for thorough SA assessments to support adequate response planning and ensure public safety.

In response, a unique calculation platform has been developed at KIT to conduct radiological dispersion studies following a severe accident at an NPP, using state-of-the-art codes for a best-estimate evaluation of the source term during an accident scenario. The CASMO5 code (Hykes, Ferrer and Rhodes, 2022) is used to determine the Fission Product (FP) inventory in the core. This data is then applied to model the NPP and analyze the postulated SA scenario from its initiation to the release of FPs into the environment, using the European reference ASTEC code (Chatelard et al., 2016), developed by IRSN. Finally, the source term data from ASTEC is used by the JRODOS code (Ievdin et al., 2010), developed by KIT, to assess the radiological consequences of the FP dispersion. This platform has been applied in previous studies (Murat et al., 2023; Murat et al., 2024) to evaluate the radiological consequences of a SBO scenario at the generic Peach Bottom Unit-2 NPP. The results of SA analyses are critical for public safety, as action plans during accidents can be developed by considering the potential consequences of these events.

The timing of failure of the barriers, the release of corium from the reactor vessel, and the passage of radionuclides through failure points can vary depending on the progression of the accident in the NPP. After determining the source term by amount and the time dependent release

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* Corresponding author.
E-mail address: onur.murat@kit.edu (O. Murat).

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rate, dispersion analysis includes dependencies in order to address safety of public and environment. Once the source term is calculated, weather conditions can also influence how the accident progresses in the environment.

After the release of radionuclides into the environment, accurately predicting their dispersion is essential for assessing public and environmental safety and implementing appropriate emergency plans. However, meteorological factors such as wind speed, wind direction, temperature, precipitation etc. introduce significant challenges to the analysis. Depending on these weather conditions, the affected areas and dose levels can vary considerably. Studies addressing this issue have highlighted that such meteorological variables are the primary sources of uncertainty in dispersion modeling and in the assessment of environmental and public safety. EU CONFIDENCE (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs) Project (2017–2019) (Raskob et al., 2020) was conducted to enhance decision-making processes, focusing on key parameters contributing to uncertainties during both the dispersion period and post-accident phases, including variations in wind patterns, the magnitude of the source term, and the timing of the event. Additionally (Van Asselt et al., 2021) explored decision-making in the transition phase after an SA, emphasizing that emergency-phase actions directly impact the return to normal living conditions. Their findings highlight the necessity of integrating emergency response and long-term recovery planning to minimize risks and ensure public and environmental safety. Therefore, a comprehensive approach that considers both immediate and long-term consequences of radiological releases is essential for effective emergency preparedness and decision-making in nuclear accidents.

The need for improved and effective emergency response planning has driven the research summarized in this paper, which further extends the calculation platform developed at KIT. This extension includes the creation of a map which includes probabilistic results of dose rate over the domain and the analysis of a large JRODOS database. The case study presented here involves the Peach Bottom Unit-2, focusing on a short-term SBO accident. The amount of radionuclides released to the environment has been taken from the previous study and this source term is simulated in JRODOS to model the emergency phase of the accident. The radionuclide release simulations are repeated to build a database for the map. The paper provides a brief description of the ASTEC model for the NPP and fuel inventory evaluation in Chapter 2. In Chapter 3, the approach for creating the map through statistical analysis is detailed, and the results are discussed.

2. ASTEC model and fuel inventory of the peach bottom unit-2

The model of the Peach Bottom Unit-2 NPP was developed using the ASTEC European reference severe accident code, and radionuclide inventory in the fuel material was determined through depletion analysis with the CASMO5 code. For this analysis, a modern BWR-type fuel assembly, GE14 10x10, was selected, with a discharge burnup of 46.47 MWd/t. The determination of the discharge burnup level and the fuel assembly's burnup period was based on experimental studies of ENRESA samples, which are from the same GE14 10x10 BWR fuel assembly type (Rochman et al., 2022; Gauld and Mertyurek, 2018; Martinez et al., 2015). It was assumed that the reactor core is loaded with fuel assemblies at the same discharge burnup level.

Detailed descriptions of the plant model, including vessel dimensions, volumes, and connections, have been provided in previous studies (Murat et al., 2023; Murat et al., 2024). Updates to the fuel assembly design and notable differences in both the fuel assembly level and the power plant level are included in this model. The core contains 764 fuel assemblies, arranged in radial meshes, and features the new GE14 10x10 fuel assembly design. Water rods in the BWR fuel assemblies improve neutron moderation, which influences the progression of accidents by increasing the availability of Zircaloy material and coolant in the active region.

The containment and reactor building zones, as well as the failure modes of primary containment, remain unchanged. These failure modes involve ruptures between the wetwell-torus and drywell-refueling bay, respectively. The reactor pressure vessel and the connections between containment sections, including failure modes and the general layout, are shown in Fig. 1. The short-term SBO scenario has been chosen for the analysis, as it is one of the highest core damage frequency accident transients for the BWR-type Peach Bottom Unit-2 NPP (U.S. Nuclear Regulatory Commission, 1990). The ASTECv3.1.1 code was used to analyze the progression of the SA scenario and evaluate the source term.

Following the failure of the head flange seals, the connection between the drywell zone and the refueling bay is activated. This leads to the transfer of radioactive isotopes from the refueling bay to the environment, initiating the release. At the conclusion of the short-term SBO simulation, a total of 2.19E18 Bq of activity was released into the environment. To put this into perspective with past severe accidents, the Chernobyl and Fukushima Daiichi incidents resulted in total radioactivity releases to the atmosphere of approximately 14.0E+18 Bq (OECD and Nuclear Energy Agency, 2003) and 6.3E+17 Bq (Institute of Nuclear Power Operations (INPO), 2011), respectively. The release of radioactive isotopes to the environment lasted for 20.68 h. At the end of the transient, the ASTEC results of radioisotopes released to the environment are provided in Table 1.

3. Statistical analysis and probabilistic dose rate distribution map

The implementation of radionuclide release from the plant to the environment, as computed by ASTEC, is a crucial step in assessing the consequences of a SA in terms of public and environmental safety, using the JRODOS code. The starting point for the release can be selected at any time during the calendar year. Depending on the chosen time period, meteorological conditions in the region may vary, including differences in wind direction, temperature, precipitation rate, etc.

To illustrate the potential consequences of radiological dispersion, example cases have been created. The release rate and the amount of released fission products remain constant across all cases. The only difference between these cases is the starting time of the release. Depending on the selected year, month, or day, the dispersion results around the NPP site can vary significantly. Not only can the day-to-day dispersion differ, but even starting the release at different times on the same day can lead to different results in terms of dispersion direction, affected area, and dose rates.

To understand the potential outcomes of the calculated radionuclide dispersion over the considered area, a statistical analysis approach, used in previous studies (Murat et al., 2023; Murat et al., 2024), has been adopted for this study as well. The grid construction consists of 8056 square meshes arranged in five concentric rings around the plant location. The outermost ring has a radius of 400 km. Meteorological data for the spatial domain under consideration were obtained from the American NOMAD servers, hosted by the U.S. National Oceanic and Atmospheric Administration (NOAA) under the U.S. National Weather Service Office. The RIMPUFF puff model was chosen for the atmospheric dispersion analysis. Simulations were conducted over a 24-hour period, which covers the full 20.68 h of radionuclide release from the power plant. The time resolution for the simulations was set to 30 min. The released activity was divided into equal 30-minute intervals to apply the time-dependent source term release, as calculated by ASTEC, in the JRODOS analyses. This time-dependent release rate allows for a more realistic analysis, as it accounts for the fact that the release of all activity at the plant is not expected to occur instantaneously. All days within the considered calendar years were taken into account, and the starting points for the release were randomly selected to simulate the radiological dispersion analysis. Among all the results, the highest recorded gamma dose rate highlighted the potential impact of the radiological release, considering a worst-case scenario with specific meteorological

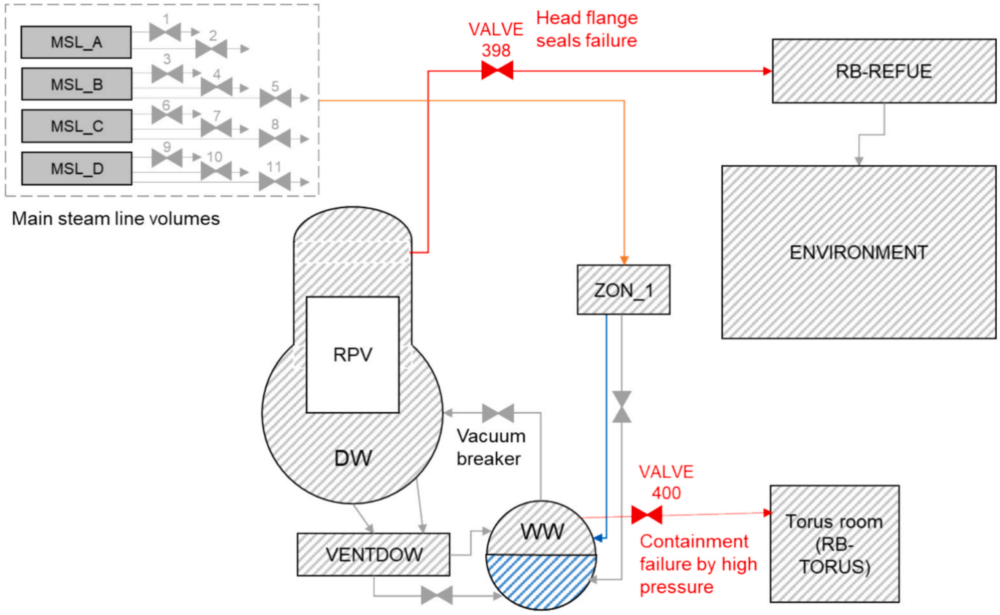

Fig. 1. Simplified representation of the containment structure of ASTEC Model of Peach Bottom Unit-2 NPP.

Table 1
Total released activities to the environment at the end of SBO transient.

Isotope	Half life	Release (Tbq)	Isotope	Half life	Release (TBq)
Kr-85	10.7 y	1.686×10^4	Mo-99	2.8 d	$13.65\ x10^2$
Sb-125	2.8 y	27.11	Rh-105	35.5 h	1.813
Sb-127	3.8 d	152.4	Ba-140	12.8 d	452.5
I-131	8.0 d	7.986×10^4	Sr-90	28.6 d	3.341
Te-132	3.2 d	1.266×10^3	Sr-91	9.5 h	3.177
I-132	2.3 h	12.34×10^3	Y-92	3.7 h	<<
Xe-133	5.2 d	1.732×10^3	Ru-103	39 d	115.9
I-133	20.8 h	7.094×10^4	Ru-105	4.4 h	1.145
I-134	0.9 h	5.698×10^{-5}	Ru-106	1.0 y	53.52
Cs-134	2.1 y	681.6	La-140	1.7 d	196.2
I-135	6.6 h	9.014×10^3	Ce-141	32 d	126.4
Xe-135	9.1 h	25.03×10^4	Ce-143	1.4 d	79.7
Cs-137	30.1 y	470.4	Ce-144	284 d	128.5

conditions. Since weather conditions vary throughout the year, month, and even day, it is necessary to evaluate every possible starting point to fully understand the potential consequences of the dispersion. To achieve this, the analysis must be performed using 1-minute time steps, which is the time resolution supported by the JRODOS code.

The followed statistical analysis simulation in the previous study (Murat et al., 2024) covered 3 calendar years, with a 24-hour analysis performed for each day of the years. The analysis was completed with a total CPU time equivalent to one day. To include every possible starting time point in the statistical analysis requires 1440 simulations per day, and the total CPU time for the 3 years of analysis would be approximately 4 years of CPU time, which is impractical to perform. Additionally, the analysis conducted for the short-term SBO accident, only considers 20.68 h of radionuclide release. Other potential accidents that could cause core damage and the release of radioisotopes to the environment might involve longer durations of fission product release, further increasing the CPU time required to complete the dispersion analysis.

To address this issue and extract meaningful information from the extensive JRODOS database, which includes 1-minute time step analyses over the years, the central limit theorem has been applied. The theorem states that, regardless of the shape of the population distribution, the distribution of the sample means will approximate a normal distribution (Dodge, 2010). For the population of time points in the year 2021, sample groups were created, and the mean distribution of these sample groups was established to approximate the population mean. The analysis was conducted separately for each season. For each season, 500 groups were selected, and radiological dispersion analyses were performed using JRODOS. Each group created by selected 30 random starting point. The total gamma dose rates were then computed and stored. The mean value of the total gamma dose rate for each group was calculated, and these 500 groups mean values were collected to establish distribution. Operation performed for every mesh point across the domain. As an example, Fig. 2 shows the distribution of the average total gamma dose rate for the sample groups at a specific mesh. It was assumed that the average of the sample group distribution for all meshes across the domain follows a normal distribution, with the mean of this distribution representing the population mean. This is equivalent to the seasonal average total gamma dose rate for each mesh.

The simulation of 500 groups, each consisting of 30 sample simulations, was completed for each season, resulting in a database of 60,000 JRODOS simulations for the year 2021. Selection of the simulation groups and sample group sizes are selected to minimize the calculation time and perform the analysis in reasonable time period. The total simulation time for these 60,000 analyses was approximately 25 days of CPU time. Simulations have been carried out in Windows environment notebook with a following specification: 24 MB cache, 8 core, 4.9 GHz Cpu and 64 GB Ram and around 1.5 TB hard drive space. The mean values of the total gamma dose rate for the winter and spring seasons are presented in Fig. 3, while the results for the summer and autumn seasons are shown in Fig. 4. Since each season has its own characteristic weather conditions, the sample groups and risk maps were constructed separately for each of the four seasons. The scale in the figure legends is set to a maximum of 50 mSv/h. Even though larger dose rates are calculated to closer sections to the NPP, choice of the limit was set 50 mSv/h since the yearly dose limit for radiation workers is 50 mSv in the U.S. (U.S. Nuclear Regulatory Commission, 1991). For the general public, the individual annual limit is set at 1 mSv.

The largest dispersion of the dose rate is observed during the winter season in Fig. 3, among all the seasons, with the main branches of the distribution located to the south, southeast, and southwest. In general, it is favorable for public safety that, not only in winter but also in spring and autumn, there is a strong tendency for dispersion towards the Atlantic Ocean, influenced by the average weather conditions. To the southwest, the cities of Baltimore, Washington D.C., and Richmond are

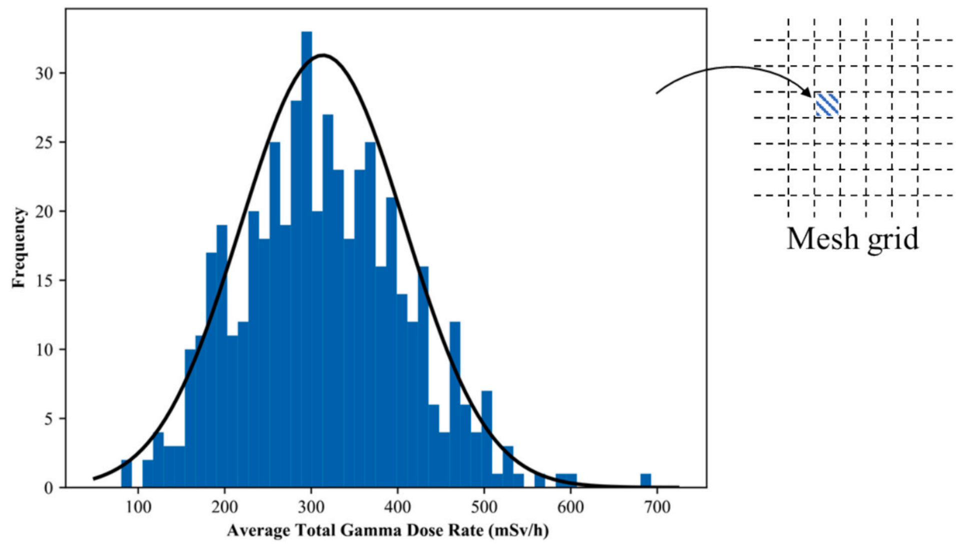

Fig. 2. Distribution of average of the sampling groups on an example mesh.

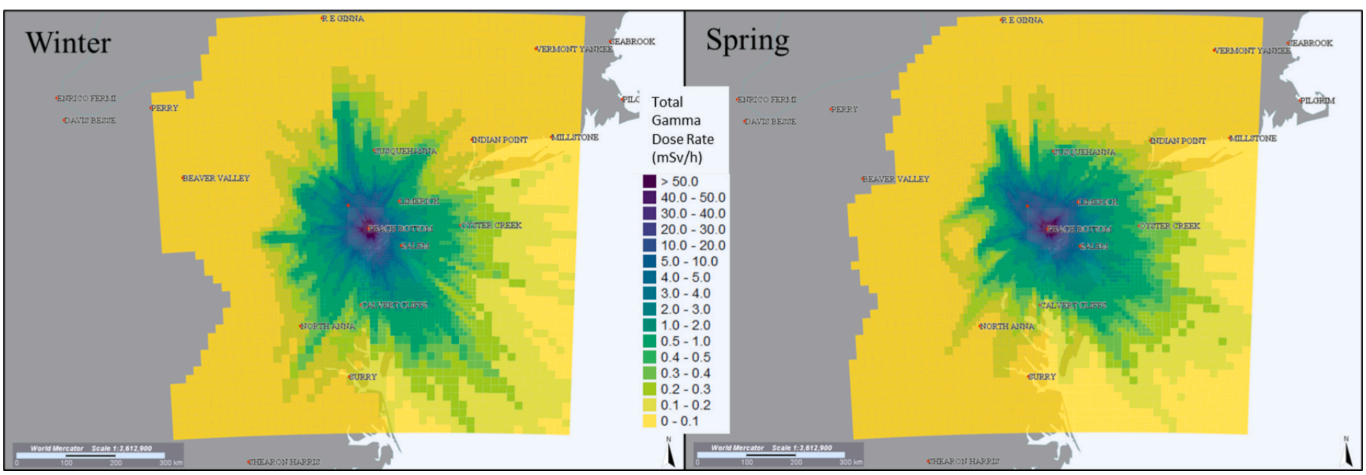

Fig. 3. Probabilistic dispersion map result of short term SBO in Peach Bottom Unit-2 NPP for seasons winter (left) and spring (right).

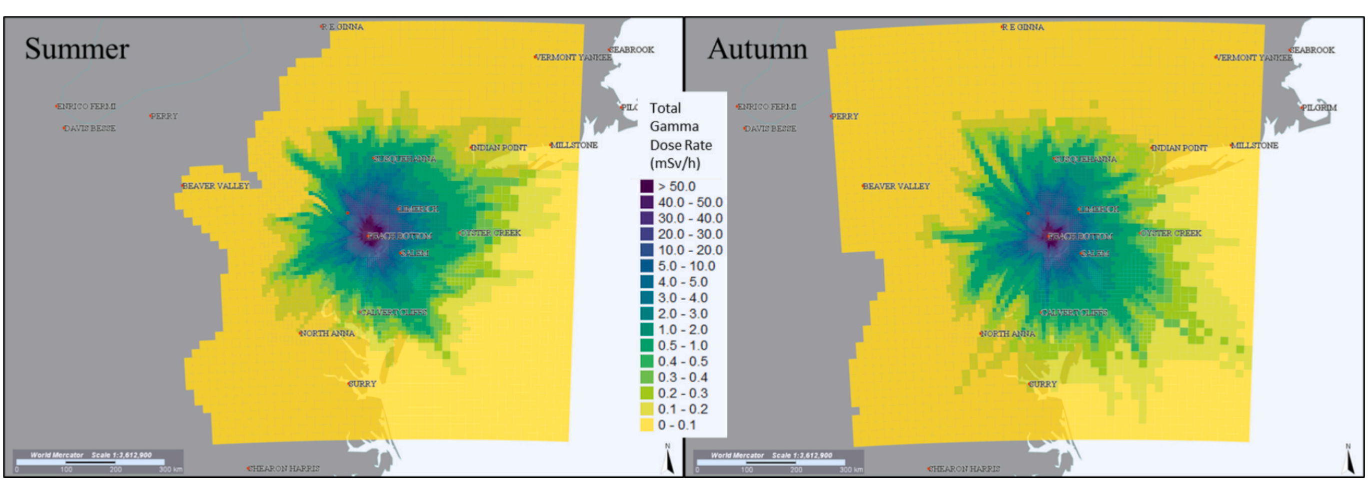

Fig. 4. Probabilistic dispersion map result of short term SBO in Peach Bottom Unit-2 NPP for seasons summer (left) and autumn (right).

located, and a widespread increase in the average total gamma dose rate is observed in both the winter, spring, and autumn maps. Additionally, a significant dispersion along the northeast direction has the potential to reach the peninsula where New York City is situated. However, the hills and mountains extending from the southwest to the northeast between the Peach Bottom Plant and Perry Nuclear Power Plant act as a barrier, preventing the spread of radioactive isotopes from progressing northward and westward.

During the summer season, the computed average total gamma dose rate exceeds the public individual limit over a larger area around the plant compared to the other seasons. Due to the typical weather conditions, the summer season generates larger high-dose rate zones. From the plant location extending up to about 38 km to the north, the recorded total gamma dose rates exceed 50 mSv/h. For comparison with previous SAs that involved radiological releases, the Three Mile Island and Fukushima Daiichi incidents are relevant. During the Three Mile Island accident, evacuation around the plant initially began with a radius of 8 km, and the evacuation area was later expanded to 32 km. A similar approach was followed at Fukushima Daiichi, where the first evacuation order covered a 2 km radius, and evacuation planning was later adjusted to extend to 10 km and eventually 20 km. The expansion of the evacuated area was due to the fact that initial plans did not account for the full extent of the accident or the magnitude of the radiological release (Ohba et al., 2021). However, by implementing the probabilistic radiological dispersion map concept for each plant, considering the worst-case scenario and potential radiological release, it is possible to determine the extent of the release and develop appropriate emergency plans. The effectiveness of communication, the number of emergency personnel, and logistical capabilities are crucial for successfully implementing the plan. At Fukushima, the station blackout disrupted communication between local and central governments, which hindered the timely and effective execution of the evacuation plan.

4. Conclusion

The Fukushima Daiichi accident highlighted the need to improve the reliability of our predictions to better support emergency plant actions. To address this issue, a calculation approach was developed to create probabilistic dispersion maps and analyze accidents with high core damage frequencies, with the ultimate goal of expanding the emergency planning database and facilitating the development of up-to-date plans. This study is a continuation of previous research, where source term calculations and SA assessments were performed using ASTEC, and statistical analyses of fission product dispersion were carried out with the JRODOS code for the short-term station blackout scenario at the Peach Bottom Unit-2 NPP. To provide an overview of possible outcomes, the total gamma dose rate parameter was chosen for the analysis. However, to better understand the radiological consequences around the plant site, additional factors such as deterministic effects, distribution of iodine tablets, evacuation and relocation of residents, long-term effects, total deposition of iodine and aerosols, and economic costs could also be included. By incorporating these factors, the constructed database can be used to update emergency planning and countermeasure actions.

A database of 60,000 JRODOS scenarios was created. The sample group size of 500 may be sufficient for some mesh points where radiological dispersion is frequent. However, for points farther from the plant, fission product transfer and dose rate readings may not be recorded in every randomly selected time frame. In rare cases, some points may not receive any measurements at all. To improve the assumption of a normal sampling distribution, the sample size can be increased. Additionally, the mesh grid around the plant was set within a 400 km radius. Beyond 300 km from the plant, the average total gamma dose rates recorded during different seasons decrease rapidly, indicating that the number of days receiving dose is low. Therefore, reducing the mesh grid size to 200 km or even smaller radiuses would help decrease computational time and yield more accurate average sampling distributions for each mesh.

It is important to note that the creation of risk maps and the assessment of possible outcomes are plant-specific, accident scenario-specific, and location-dependent. Even with the same design and accident or similar source term release in terms of activity and release rate, results can vary by geographical location. Conducting probabilistic map analyses for a fleet of power plants nationwide could help identify regions with higher potential risks to public safety. The methodology described in this paper will be applied to other generic SA scenarios and different NPP designs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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