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A study on the RIMPUFF module (ARGOS) and simulation of radiation dispersion from a hypothetical floating nuclear power plant accident in the East Sea

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Abstract: In this study, the RIMPUFF module (ARGOS) was used to simulate the Fukushima-Daiichi nuclear power plant accident (FNPPA), thereby assessing the research team’s capability in using the program. The FNPPA simulation results showed good agreement in trend and intensity with the environmental monitoring data and other simulation models. Based on these results, our research team used RIMPUFF to simulate the atmospheric dispersion from the hypothetical accident of a floating nuclear power plant operating in the East Sea (Phu Lam Island, the Paracel Islands, Da Nang Province, Vietnam), through which we analyzed the accident’s impacts on the Vietnamese mainland territory. Depending on weather conditions and specific locations, the impact area of the accident varies. Under conservative conditions, the wind blowed from the East Sea at a speed of 7.5 m/s, the radioactive cloud would reach the mainland territory (Quang Tri and Quang Binh provinces) approximately 15 hours after the accident. Subsequently, the accident created an area of hundreds of square kilometers, with dose rate greater than 1 μSv/h; I-131 and Cs-137 deposition on the ground would exceed 10 kBq/m^2 and 2 kBq/m^2, respectively. According to the regulation on preparedness and responses to nuclear and radiological emergencies, people in the affected areas must immediately stop consuming local food and milk until the result of sample examination is available. The study results demonstrate the ARGOS usability and its value in supporting decision-making in the nuclear accident emergencies.

Keywords: *RIMPUFF, ARGOS, radioactive dispersion, simulation, floating nuclear power plant.*

I. INTRODUCTION

Currently, the operations of China's nuclear power plants (NPPs) near the northern border of Vietnam, such as Fangchenggang and Changjiang NPPs, require the tasks of radiation monitoring, serving both early warning and decision support in emergency situations. To support these monitoring activities, simulations of atmospheric radioactive dispersion have been conducted in recent research projects in Vietnam [1], [2], [3]. Furthermore, China is also pursuing the trend of developing floating nuclear power plants (FNPPs), and the feasibility of operating this technology in the East Sea is considered potential [4]. One of China's developing FNPP technologies is the ACPR50S, which originates from the Russian KLT40S reactor technology [5]. This technology is the subject of investigation and source term development for simulating

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radioactive dispersion from a hypothetical FNPP incident in the East Sea in this study.

ARGOS (Accident Reporting and Guiding Operational System) is a simulation and decision support tool for emergency response [6], widely used in European, Australian, American, and other countries. The RIMPUFF module, a component of ARGOS, is used for medium-range dispersion simulation [7], and it will be used to simulate the Fukushima NPP accident [8] before being used to simulate the ACPR50S FNPP incident in the South China Sea.

II. METHODOLOGY

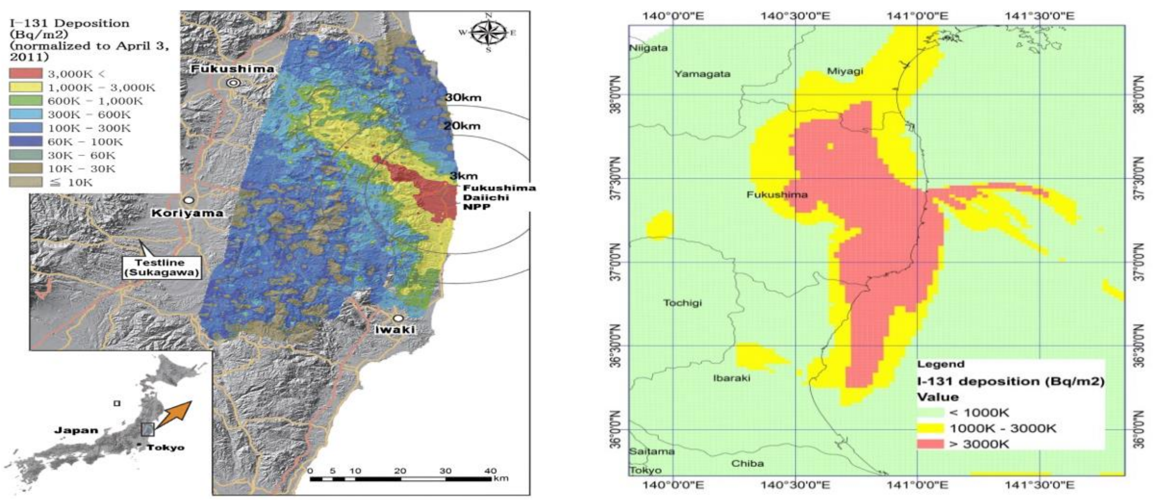
A. Simulation tool: RIMPUFF module

RIMPUFF (Risø Mesoscale PUFF model) is a Lagrangian mesoscale atmospheric dispersion puff model, designed to determine the concentration and doses resulting from the dispersion of airborne materials [7]. The model can be applied to both homogeneous and inhomogeneous terrain with moderate topography on horizontal scale; and it responds to changing meteorological conditions. It simulates the time-varying releases of airborne materials by sequentially releasing a series of Gaussian shaped puffs at a fixed rate on a specified grid. RIMPUFF system is a part of the ARGOS2000 Decision Support System, and Institute for Nuclear Science and Technology (INST, VINATOM) has been a user group member since 2019. In 2021, Duong Duc Thang et al. [1] used ARGOS to simulate atmospheric radioactive dispersion from the hypothetical Fangchenggang NPP accident affecting Vietnam. Therefore, RIMPUFF is a tool to estimate the source term from 200 MWt Small Modular Reactor (SMR) accident and to simulate of the dispersion of radioactive nuclei in the air environment.

B. FLECHT-SEASET Tests

The RIMPUFF module (ARGOS) was used to simulate the Fukushima-Daiichi (FDNPP) incident in Japan in 2011. The source terms of the Fukushima incident were provided by Tereda et al.,[9]; and the meteorological data, in numerical format, were shared by the ARGOS program development team [10].

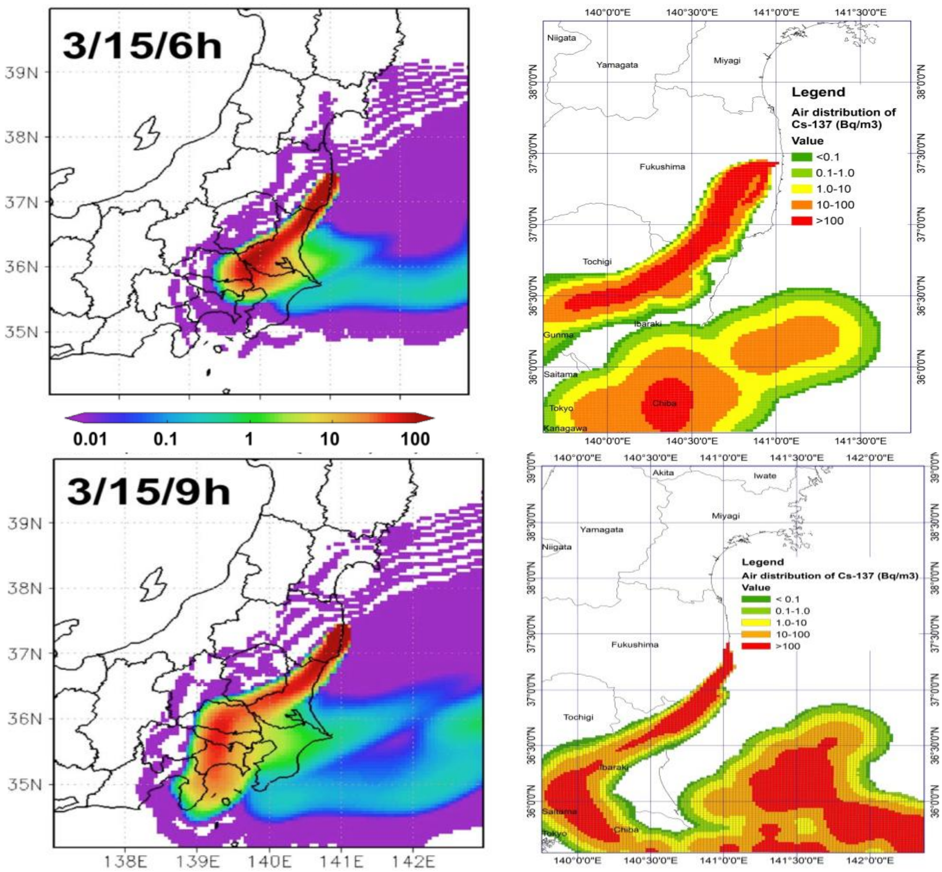
These data were used to simulate the FDNPP incident by RIMPUFF module. The simulation results showed good agreement with both the trend and intensity of the measurement data [11], and in other simulation models [12], as shown in Figure 1 and Figure 2. This serves as the basis for the research group to conduct simulations of the hypothetical ACPR50S incident.



(a) Ground concentration of I-131 (Bq/m^2) at 3 April 2011 [11]

(b) Simulation result by RIMPUFF (ARGOS)

Fig. 1. Comparison of the measurement and simulation data of I-131 (Bq/m2) in FDNPP



N-model [12] RIMPUFF (ARGOS)

Fig. 1 Comparison of air distribution of Cs-137 (Bq/m^3) results by N-model [12] and RIMPUFF (ARGOS)

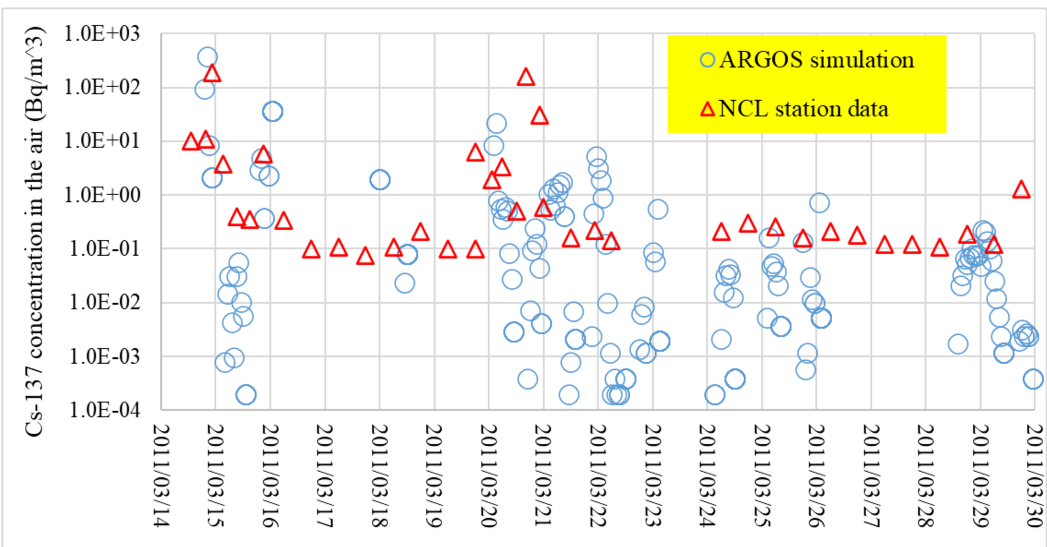


Fig. 2. The comparison of NCL station data in Tokai-Mura [13] and RIMPUFF (ARGOS) simulation results in Cs-137 concentration in the air (Unit: Bq/m^3)

As shown in Figure 3, almost all instances of radioactive plumes reaching the emergency monitoring of the environmental radiation at Nuclear Fuel Cycle Engineering Laboratories (NCL), Japan Atomic Energy Agency [13], were detected on the 15th, 16th, 20th, and 21st days of March 2011. The simulation values exhibited variations compared to the measured values due to spatial averaging in the computational program, demonstrating the consistency between measurement results and simulations.

C. Estimation of ACPR50S source terms

Commonly, data related to Chinese reactor technology is often challenging to access. Based on the developmental origin of ACPR50S from the Russian KLT40S technology [5], [14], this research first determines the source term of KLT40S, and then extrapolates to derive the source terms of ACPR50S.

The scenario for the FNPP's KLT40S incident involves a significant rupture in the reactor cooling system (LOCA), resulting in an explosion, causing the meltdown of the reactor core and damaging the reactor containment vessel, leading to the release of radioactive materials up to a height of 20 meters [15]. The ARGOS system is capable of estimating source terms for Light Water Reactors (LWRs) based on input parameters such as reactor technology, thermal power, and accident scenarios, using the Probabilistic Safety Assessment (PSA) method to calculate release levels [16]. For Pressurized Water Reactors (PWRs), there are 9 accident levels labeled as PWR1 to PWR9, with decreasing release levels of Xe-Kr, I, Cs-Rb, Ba-Sr, Ru, and La isotopes, presented as percentages of the inventory of these isotopes in the reactor core. According to [16], the maximum release level can reach 70% for I-131, 50% for both Cs-137 and Cs-134.

Table I. The source terms for KLT40S and ACPR50S in LOCA accident by ARGOS and RASCAL tools (Unit: Bq)

	KLT40S (150 MWt)			**ACPR50S (200 MWt)**	
Isotopes	ARGOS	RASCAL	[15]	ARGOS	RASCAL
Cs-134	7.05E+15	1.1E+16	5.51E+17	9.40E+15	2.2E+16
Cs-137	6.01E+15	7.9E+15	1.74E+18	8.01E+15	1.5E+16
I-131	1.02E+17	4.9E+16	3.29E+15	1.36E+17	7.0E+16
Equivalent to I-131	4.62E+17	5.5E+17	2.29E+18	6.16E+17	1.0E+18

Another tool with the capability to determine the source terms of nuclear power plants is the RASCAL program [17], developed by the U.S. Nuclear Regulatory Commission. The accident scenarios in RASCAL can be described in more detail compared to the source term models of ARGOS. Specifically, damage amount of fuel cladding, reactor core, reactor vessel, containment, and the operation of safety systems (such as the suppression spray system inside the containment) can be described in the input data.

Based on the accident scenario described in Berge et al. [15], the corresponding source terms for KLT40S were calculated using the ARGOS and RASCAL tools, and the results are presented in Table I. The three isotopes of the greatest concern related to the source term , Cs-134, Cs-137 and I-131 [18], are listed in Table I and converted to an equivalent value to I-131 [19]; to assess the calculation results. The calculated source term values equivalent to I-

131 by ARGOS and RASCAL are 4.62E+17 Bq and 5.5E+17 Bq respectively, both of which are smaller than the source term calculated by Berge et al., due to the conservative assumption that the KLT40S FNPP was in full power for 3 years, before the accident occurred. Thus, the ARGOS and RASCAL tools have successfully determined the source term for the KLT40S FNPP with an acceptable level of accuracy. These tools were then used to estimate the source term for the ACP50S FNPP using the same accident scenario. The results, as presented in Table II, show that the source term determined by RASCAL (1.0E+18 Bq) is larger than ARGOS (6.16E+17) due to its more detailed input data in the calculations. To ensure conservatism in the safety analysis, the larger source term (RASCAL) is used to simulate the hypothetical accident when the ACPR50S FNPP operates “illicitly” on Phu Lam Island, part of the Paracel Islands, Da Nang Province, Vietnam, as discussed in the next section.

The International Nuclear and Radiological Event Scale (INES) was developed in 1990 by international experts convened by the IAEA and the OECD Nuclear Energy Agency (OECD/NEA) with the aim of communicating the safety significance of events at nuclear installations [20]. There are 7 levels in the INES scale, with levels 4 to 7 classified as accidents and levels 1 to 3 classified as incidents. In this research, the release mount of 1.0E+18 Bq is equivalent to a major accident, corresponding to level 7 on the INES scale.

D. Other input data

Based on meteorological data recorded in Da Nang in 2022 [21], the time with the highest wind speed and the wind direction from the East Sea towards the Vietnam mainland was chosen as the time for the hypothetical accident. According to these criteria, the time at 00:00 on October 15, 2022, when the wind speed reached 7.5 m/s with a westward direction, was chosen as the time for simulating the hypothetical incident.

ARGOS uses Numerical Weather Prediction (NWP), a set of meteorological data that is continuously forecasted up to 99 hours ahead in real time. The national meteorological service generates NWP data from a model of the atmosphere called HIRLAM (High Resolution Limited Area Model). HIRLAM is the result of the research cooperation of European meteorological institutes [22]. In this report, the simulated area’s meteorological data covers a range of longitude 85.5–150.5° E and a latitude range of 2.5–59.5° N, with a resolution of 0.250 × 0.250.

Terrain data: Topographic data, including elevation maps, land use maps, soil maps, and population density, are updated regularly. Maps with a resolution of 25 km × 25 km in the simulation area were all generated in GeoTIFF format[23].

III. RESULTS AND DISCUSSION

A. Results

The radioactive plumes affected the mainland territory of Vietnam 15 hours after the incident, and after 18 hours, it moved out of Vietnam's territory into Laos. The movement of the radioactive plume is shown in Figure 4.

Upon entering the territories of Quang Tri and Quang Binh provinces, the radioactive plumes created an area with a dose rate exceeding1 μSv/h. Subsequently, this affected area continued to expand as the plume progressed. Additionally, due to the deposition process, the activity concentrations of I-131 and Cs-137 exceeded the thresholds of 2 kBq/m2 and 10 kBq/m2, respectively, as shown in Figure 5 and Figure 6.

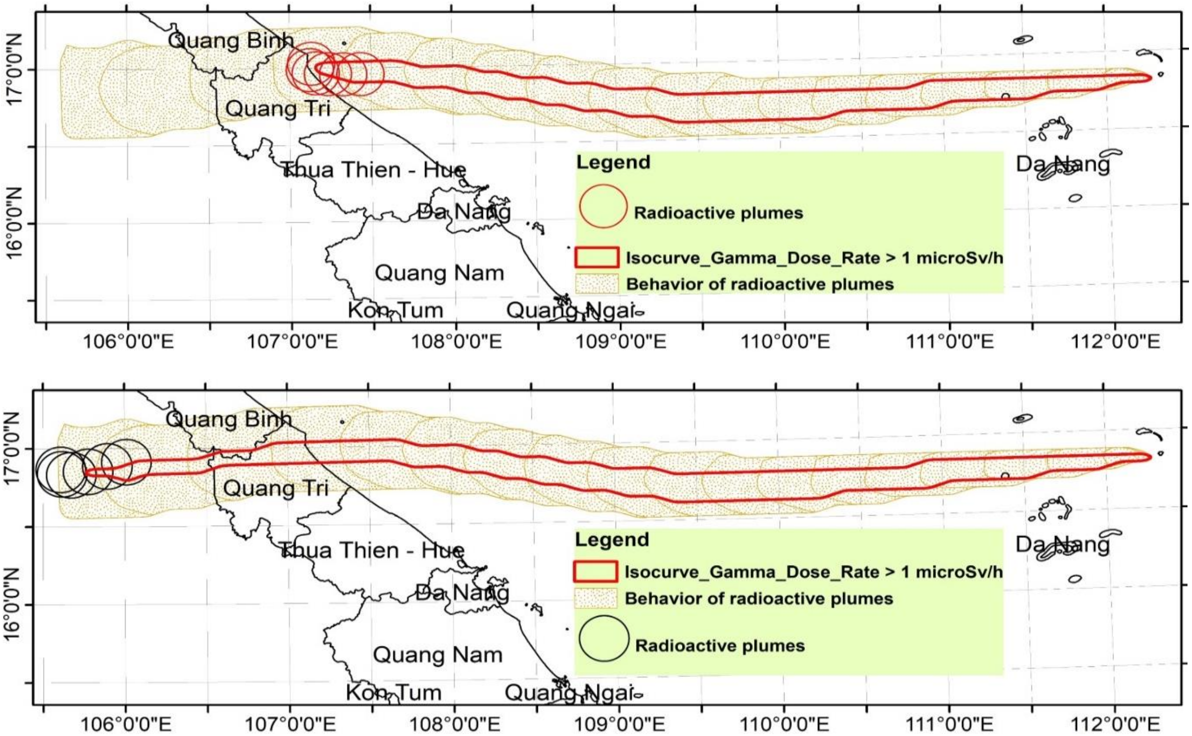
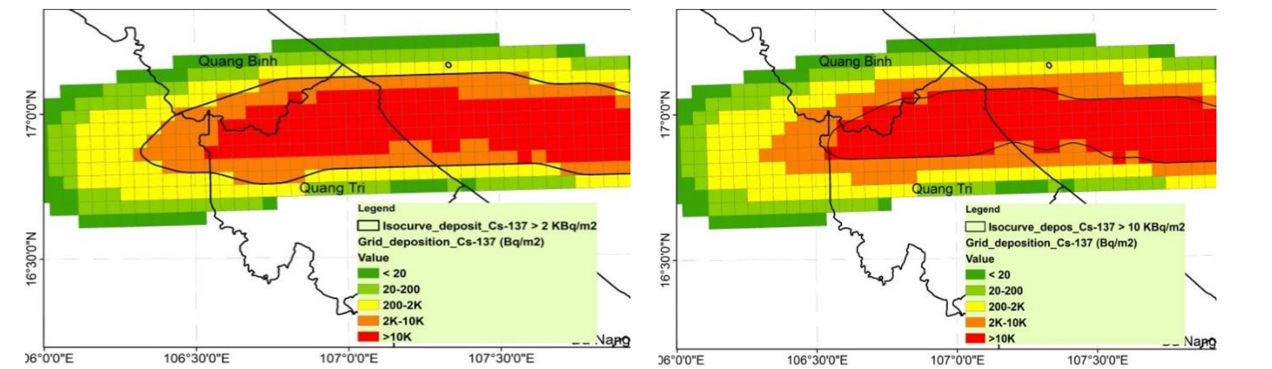
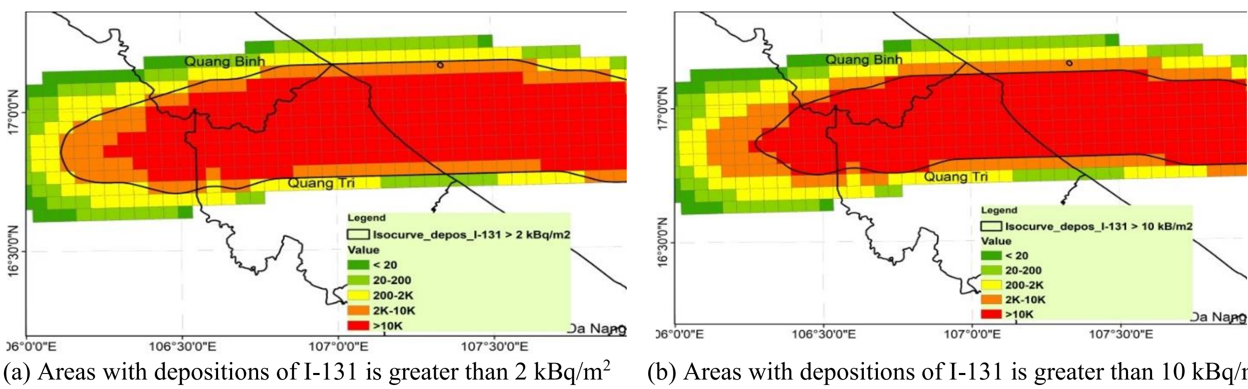


Fig. 3. Behavior of radioactive plumes and area's gamma dose rate is greater than 1 microSv/h



(a) Areas with depositions of Cs-137 is greater than 2 kBq/m^2 b) Areas with depositions of Cs-137 is greater than 10 kBq/m^2

Fig. 4 Areas with depositions of Cs-137 are greater than 2 kB/m^2 and 10 kBq/m^2.



(a) Areas with depositions of I-131 is greater than 2 kBq/m^2 (b) Areas with depositions of I-131 is greater than 10 kBq/m^2

Fig. 5. Areas with depositions of I-131 are greater than 2 kB/m^2 and 10 kBq/m^2.

B. Discussion

According to Circular 25/2014/TT-BKHCN, regarding the response plan for radiation and nuclear incidents [24], if the dose rate exceeds 1 µSv/h, or if the activity concentration of I-131 exceeds 10 kBq/m2, or Cs-137 exceeds 2 kBq/m2, the consumption of food and milk in that area must be immediately stopped until sample testing results are available, as detailed in Table II. The simulation results show areas with parameters exceeding the thresholds, providing the reference information for sample collection and analysis, if necessary.

Table II. Operational intervention levels (OIL) based on radiation values measured in the air and food [24]

Radiation sources	Ordinal numbers (OIL)	Default value		Protective actions
Dose rate in the air (measured at one meter height from ground)	1	1 mSv/hour		Evacuation or sheltering
	2	0,2 mSv/hour		Considering evacuation of people from the area
	3	1 µSv/hour		Immediately stop consumption of food and milk in the area until the result of sample examination is available.
Dose rate on ground surface		**Normal food**	**milk**	Immediately stop consumption of food and milk in the area until the result of sample examination is available.
I-131	4	10 kBq/m^2	2 kBq/m^2	
Cs-137	5	2 kBq/m^2	10 kBq/m^2	

Due to the distance from Phu Lam Island to Quang Tri, approximately 550 km, the activity concentration of radioactive isotopes significantly decreases during the dispersion process, and immediate evacuation of the population is not required. However, under more severe weather conditions with higher wind speeds and wind directions causing the dispersion of radioactive material towards mainland areas closer, such as Da Nang, Quang Nam, Quang Ngai, and Binh Dinh provinces (within a distance of over 400 km), the consequences of the incident would be more severe.

IV. CONCLUSIONS

In the context of many NPPs that have been or will be constructed in neighboring countries, the utilization of the ARGOS simulation program supports ongoing radiation monitoring activities in Vietnam and facilitates decision-making in emergency response situations. The research has successfully assessed the program's usability, established source terms for a new technology (ACPR50S FNPP) that could be deployed in the East Sea, and simulated a hypothetical incident involving the operation of a floating nuclear power plant in Phu Lam island, the Paracel Islands, Da Nang Province, Vietnam. Consequently, it provides an initial assessment of the potential impact of such an incident;

The hypothetical incident at the ACPR50S FNPP could result in a level 7 accident, the highest level on the INES scale. Under meteorological conditions on October 15, 2022, the incident would primarily impact the territories of Quang Tri and Quang Binh provinces with hundreds of square kilometers experiencing air dose rates exceeding 1 μSv/hour. The phenomenon of fallout leads to the appearance of areas with concentrations of Cs-134 and I-131 exceeding 2 kBq/m2 and 10 kBq/m2, respectively. According to Circular 25 [24] “Immediately stop consumption of food and milk in the area until the result of sample examination is available”.

The simulation results help provide a preliminary assessment of the potential impact of the accident on the mainland territory of Vietnam; They assist in decision-making for emergency response and support sample collection and analysis activities for further response actions. The simulation results provide information to support the selection of locations and the installation of radiation monitoring and early warning systems.

Future works

The rapid and accurate determination of the source term value and characteristics contributes to better dispersion modeling results, thereby supporting quicker incident response. Therefore, researching, updating, and collecting data on the reactor technology of countries in our region, as well as new technologies like SMR and FNPP, is particularly necessary. This helps determine the emission levels, composition, and state of isotopes, as well as the release height of radioactive materials into the environment. These objectives will form the focus of our research team’s future work.

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