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Using ARGOS to simulate radioactive dispersion in the atmosphere from Fangchenggang nuclear power plant to Viet Nam

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Abstract: In this study, ARGOS software was used to simulate the atmospheric radioactive emissions from Fangchenggang nuclear power plant to Viet Nam. The simulated cases are hypothetical accidents with hypothetical source terms equivalent to level 6 of the International Nuclear and radiological Event Scale (INES). The results show the possibility of using ARGOS in simulating atmospheric dispersion, assessing radiation dose to humans from the Fangchenggang nuclear power plant accident to Viet Nam in some accident situations. Furthermore, the obtained results contribute to forecasting and supporting emergency response when an accident occurs in nuclear power plants.

Keywords: *ARGOS, Fangchenggang nuclear power plant, Atmospheric dispersion*.

I. INTRODUCTION

In recent years, China's nuclear power industry has developed rapidly. In 2020, China had 49 nuclear reactors in operation with a total capacity of 47.5 GW and 14 reactors under construction with 14.2 GW [1]. Notably, many Chinese nuclear power plants (NPPs) have been built near the northern border of Viet Nam, such as Fangchenggang NPP in Guangxi province and Changjiang NPP in Hainan Island. These nuclear power plants use 2nd generation nuclear reactor technology with low safety factor requirements [2]. Currently, units 1 and 2 of Fangchenggang NPP (with a capacity of 1000 MW each) are in commercial operation [1,2]. The distance from Fangchenggang NPP to Quang Ninh province of Viet Nam is only about 50 km in the upstream wind direction. Therefore wind tends to blow from the NPP toward Viet Nam, especially in winter [2].

According to the International Atomic Energy Agency (IAEA) recommendation, for NPP with a capacity of over 1000 MW, within a radius of 300 km from the NPP, an emergency response plan to major accidents that may occur from these plants must be developed [2,3].

Lessons learned from the March 2011 Fukushima NPP accident show the importance of environmental radiation monitoring, simulation, calculation, and assessment of radioactive material released from NPP in preparing and responding to radiation and nuclear accidents, especially for severe accidents that may occur during the operation of NPP. During the accident, Japan and other countries made calculations and forecasts on the effects of radioactive plumes from Fukushima to other areas of Japan and other countries. The results of those forecasts have helped Japan and other countries to make appropriate decisions in the event of an accident [2].

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Currently, there are many software or programs (collectively referred to as software) to calculate radioactive dispersion in the air in both regular operation and accident of NPP that is quite popular in the world, such as HYSPLIT, FLEXPART, AERMOD, CALPUFF, NRCDose72, RASCAL, ROSDOS, and ARGOS… [4]. Recently, in Viet Nam, there have been many studies on simulation software to assess atmospheric radioactive dispersion. For example, NRCDose72 software has been used to assess radioactive emissions under normal operating conditions, serving NPP licensing [5, 6]. In addition, FLEXPART has been used to simulate long-range radioactive dispersion from NPPs near the border of Viet Nam [2,4]. This study used ARGOS software to simulate and assess atmospheric radioactive dispersion.

ARGOS software was proposed to be built and developed in 1986 after the Chernobyl accident, with the goal of emergency response in cases of disasters related to nuclear, biological, and chemical. In 2008, at the 12th Congress of the International Radiation Protection Association (IRPA 12), ARGOS was assessed by the IAEA as an effective tool in supporting decision-making in emergency response to nuclear accidents. ARGOS continues to evolve to build a fully integrated database of radioactivity monitoring, atmospheric dispersion simulation, and dose calculation functions. ARGOS has been commercialized and widely used in many countries, including Viet Nam. Advantages of ARGOS are the ability to synchronize meteorological data for the next 99 hours in real-time, detailed calculation time of several hours, the ability to give many parameters related to radiation exposure to people (of various ages) and pollution of soil, air, and plants; allowing the user to have an overall view of the impact of a nuclear accident on the surrounding environment [8].

This report presents the use of ARGOS software for simulating radiation dispersion, assessing radiation dose to humans from a hypothetical accident of Fangchenggang NPP in Viet Nam, supporting the management agency in forecasting and responding to radiation and nuclear accidents.

II. MATERIALS AND METHODS

In this report, ARGOS version 9.9 was used to simulate the dispersion of radionuclides with source terms equivalent to level 6 in the International Nuclear and Radiological Event Scale. The emission source is from a hypothetical accident from Fangchenggang NPP to Viet Nam under the extreme meteorological scenario.

A. ARGOS – the dispersion calculation model

ARGOS uses the RIMPUFF (Risø Mesoscale PUFF model), which is a Lagrangian mesoscale atmospheric dispersion puff model used in calculating the concentration and doses resulting from the atmotspheric dispersion of radioactive materials. The model could be used for the dispersion calculation for unstable and inhomogeneous meteorological conditions. RIMPUFF model is usually used to estimate the consequences of the short-term (accidental) atmospheric release of radioactive materials [8]. In addition, the model could be applied in both homogeneous and inhomogeneous terrain with moderate topography on a horizontal scale of up to 100 km. Also, the model could responds to changing (nonstationary) meteorological conditions [8].

B. Meteorological data

ARGOS uses Numerical Weather Prediction (NWP), a set of meteorological data that is continuously forecasted up to the next 99 hours from 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 [9].

This report's simulated area meteorological data has a range of longitude 90–127° E and latitude 3–29° N, with resolution $0.25^0 \times 0.25^0$.

C. Terrain data

Topographic data, including elevation maps, land use maps, soil maps, and population density, are updated regularly. Maps with a resolution of 1km × 1km in the European area and 25 km × 25 km in the other region were all generated as GeoTIFF [7].

D. Source term

RASCAL (Radiological Assessment System for Consequence AnaLysis) is a software developed and used by the Office of Nuclear Security and Incident Response of the United States Nuclear Regulatory Commission to assess radiation dose in the event of a nuclear accident. We use the RASCAL4.3 version to build the source term in a nuclear power plant accident, serving the dispersion calculation in this study [6].

Input data includes NPP technology characteristics (Pressurized water reactor), reactor power (2905 MW-thermal) and accident scenario (LOCA and containment damage). The radionuclide inventory was estimate, and following the LOCA (Loss of cooling accident), fuel material and reactor vessel were melted [7]. The release mount was calculated with leak rate of 10%/h through the containment failure [7], the detail source term was showed in Table I.

Table I. Radionuclides released into the environment in the event of a level 6 accident

Radionuclide	Activity (Bq)	Radionuclide	Activity (Bq)	Radionuclide	Activity (Bq)
Am-241	4.8E+05	Mo-99	1.4E+13	Sr-91	3.1E+13
Ba-139	3.2E+11	Nb-95	1.1E+12	Sr-92	3.7E+12
Ba-140	1.2E+14	Nb-95m	7.5E+08	Tc-99m	1.3E+13
Ce-141	2.8E+12	Nb-97	3.7E+10	Te-127	1.6E+13
Ce-143	2.0E+12	Nd-147	4.3E+11	Te-127m	2.5E+12
Ce-144*	2.2E+12	Np-239	3.1E+13	Te-129	6.9E+12
Cm-242	2.8E+10	Pm-147	1.7E+08	Te-129m	1.1E+13
Cs-134	6.2E+14	Pr-143	1.0E+12	Te-131	5.8E+12
Cs-136	1.2E+14	Pr-144	1.9E+12	Te-131m	2.6E+13
Cs-137*	4.3E+14	Pu-238	7.3E+05	Te-132	2.2E+14
Cs-138	2.2E+09	Pu-239	1.4E+06	Xe-131m	4.1E+14
I-131	2.5E+15	Pu-241	4.2E+11	Xe-133	5.9E+16
I-132	2.4E+15	Rb-86	4.4E+12	Xe-133m	1.7E+15
I-133	3.5E+15	Rb-88	5.9E+14	Xe-135	1.9E+16
I-134	8.0E+11	Rh-103m	1.4E+13	Xe-135m	4.3E+14
I-135	1.4E+15	Rh-105	7.9E+12	Xe-138	2.4E+02
Kr-83m	2.4E+13	Ru-103	1.4E+13	Y-90	2.7E+11
Kr-85	5.0E+14	Ru-105	1.4E+12	Y-91	8.4E+11
Kr-85m	8.7E+14	Ru-106*	7.6E+12	Y-91m	1.0E+13
Kr-87	1.3E+13	Sb-127	1.4E+13	Y-92	1.2E+12
Kr-88	7.4E+14	Sb-129	7.7E+12	Y-93	2.7E+11
La-140	5.2E+12	Sr-89	6.1E+13	Zr-95	1.1E+12
La-141	1.3E+11	Sr-90	9.4E+12	Zr-97*	6.4E+11

E. Survey and selection of simulation time

According to a survey by Project KC.05/16-20, "The Siberian high pressure, originating from the northeast monsoon, affects strongly Viet Nam 's northern region in November, December, January, and February" [2]. Therefore, we chose the days with the highest wind speed from October 2020 to March 2021 to preliminarily study the impact of the hypothetical accident. Meteorological data at Nanning station (China) was used to identify days with "extreme" weather [10]. We chose the days with the strongest wind from the survey results as 8:00 am (UTC) on October 15, 2020, and 4:00 pm (UTC) on March 1, 2021.

III. RESULTS AND DISCUSSION

We use ARGOS software to simulate the atmospheric radioactive dispersion from the hypothetical accidents at Fangchenggang NPP to Viet Nam. The first accident took place at 8:00 am on October 15, 2020, and the second accident took place at 8:00 am on March 1, 2021, with a source term equivalent to a level 6 accident on the INES scale.

A. First Accident Scenario

The first accident scenario was a hypothetical accident that occurred at Fangchenggang NPP at 8:00 am (UTC) on October 15, 2020, with an emission time of 2 hours.

After 3 hours, the radioactive plume emitted from Fangchenggang NPP reached Quang Ninh province, the plume's center towards Mong Cai city. The activity concentration of I-131 was distributed quite concentratedly. The highest activity concentration of I-131 was 4700 Bq/m^3 (Figure 1). The plume of Cs-137 was similar to that of I-131, with the highest value of 741 Bq/m^3 (Figure 2).

After 23 hours, the radioactive plume has gone out of Viet Nam, and the center of the radioactive plume has covered part of the provinces: Quang Ninh, Lang Son, Bac Giang, Thai Nguyen, Bac Can, Vinh Phuc, Phu Tho, Tuyen Quang, Yen Bai, Lao Cai, Lai Chau, Son La, and Dien Bien. The activity concentration of I-131 is shown in Figure 3. The highest activity concentration of I-131 was 13.9 Bq/m^3. The activity concentration of Cs-137 was similar to that of I-131 (Figure 4), and the highest value was 2.56 Bq/m^3.

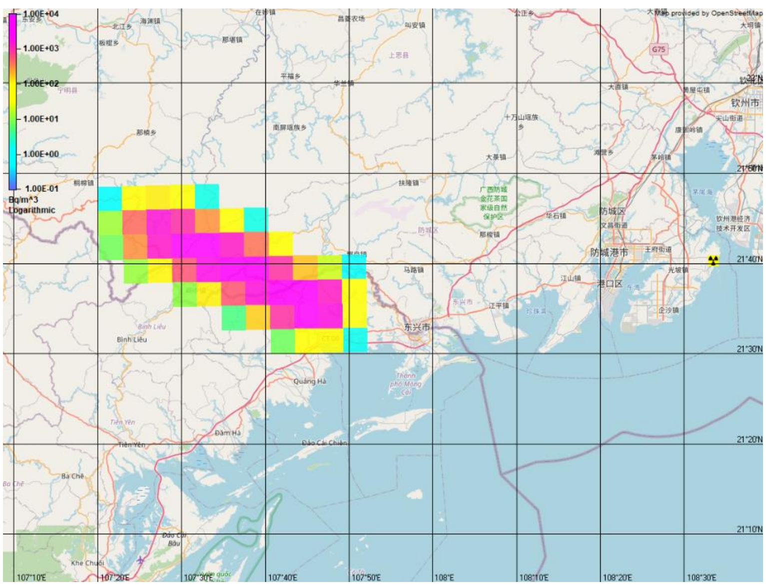

Fig. 1. Distribution of the activity concentration of I-131 after 3h from the first accident scenario

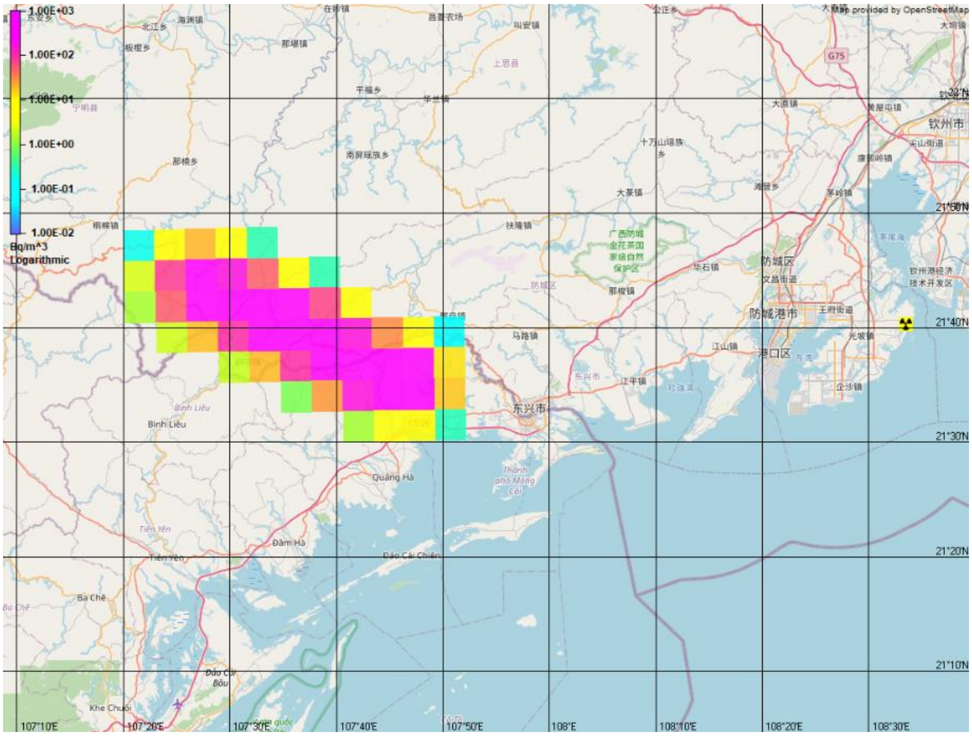

Fig. 2. Distribution of the activity concentration of Cs-137 after 3h from the first accident scenario

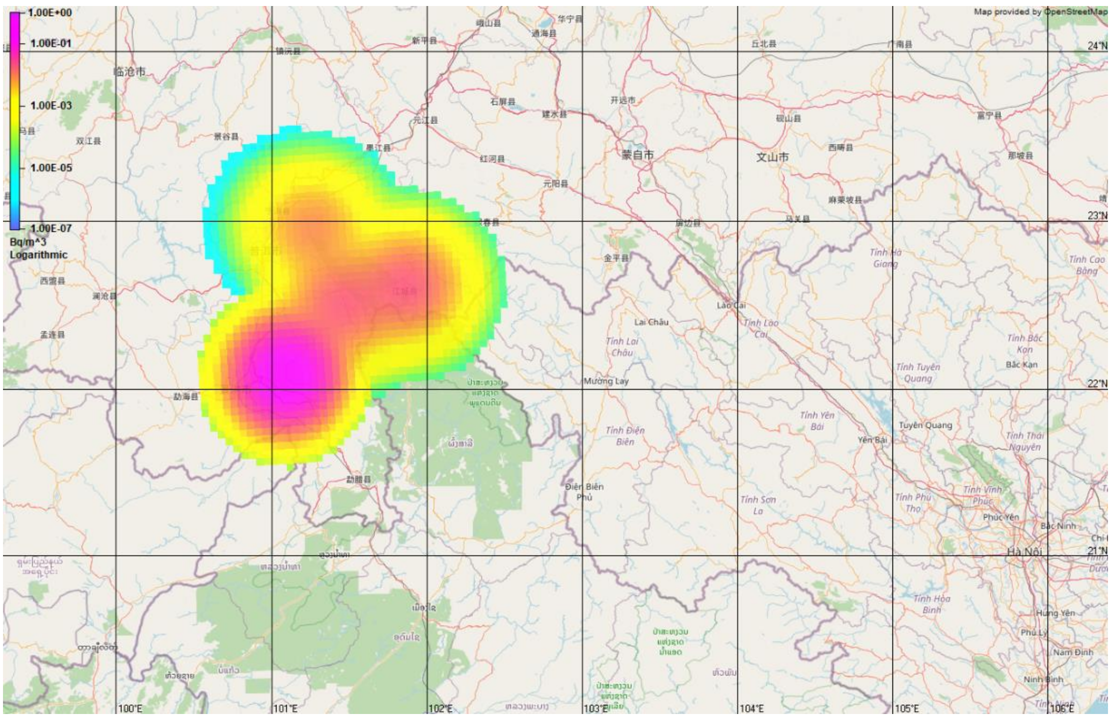

Fig. 3. Distribution of the activity concentration of I-131 after 23h from the first accident scenario

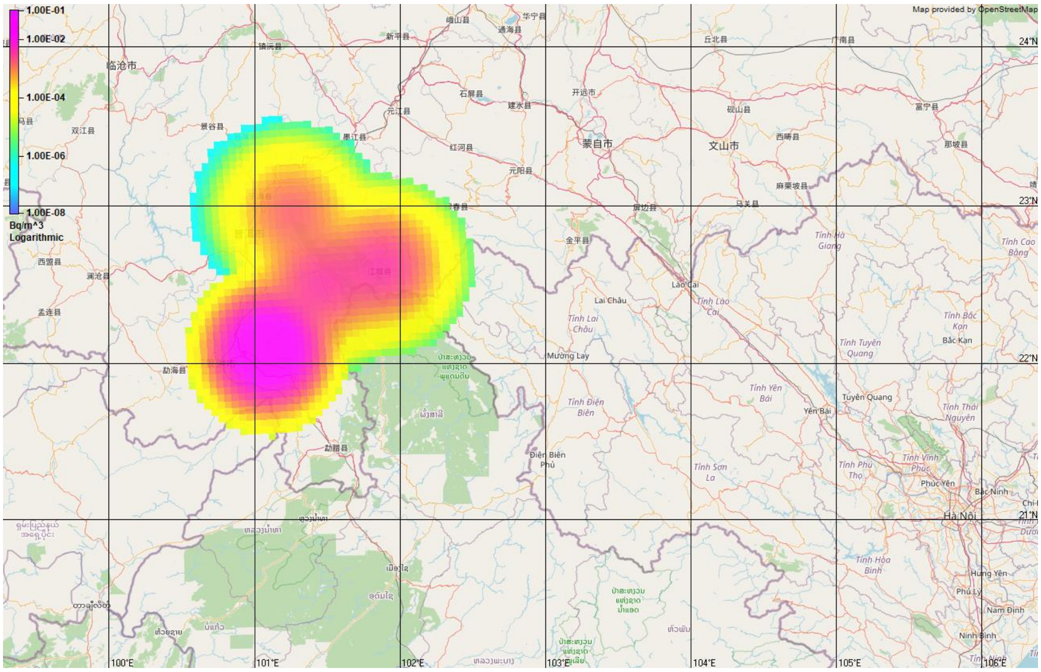

Fig. 4. Distribution of the activity concentration of Cs-137 after 23h from the first accident scenario

The deposition distribution of radionuclides I-131 and Cs-137 after 23h is shown in Figure 5 and Figure 6. The highest deposition of radionuclides I-131 and Cs-137 in Viet Nam is 6.79E5 Bq/m^2 and 1.02E5 Bq/m^2, respectively. For the areas where the deposition of I-131 is greater than 10 kBq/m^2 and the deposition of Cs-137 is greater than 2 kBq/m^2, local food consumption must be stopped until the analysis results of radionuclides I-131 and Cs-137 are available to determine whether they are lower than the allowable limits. [11].

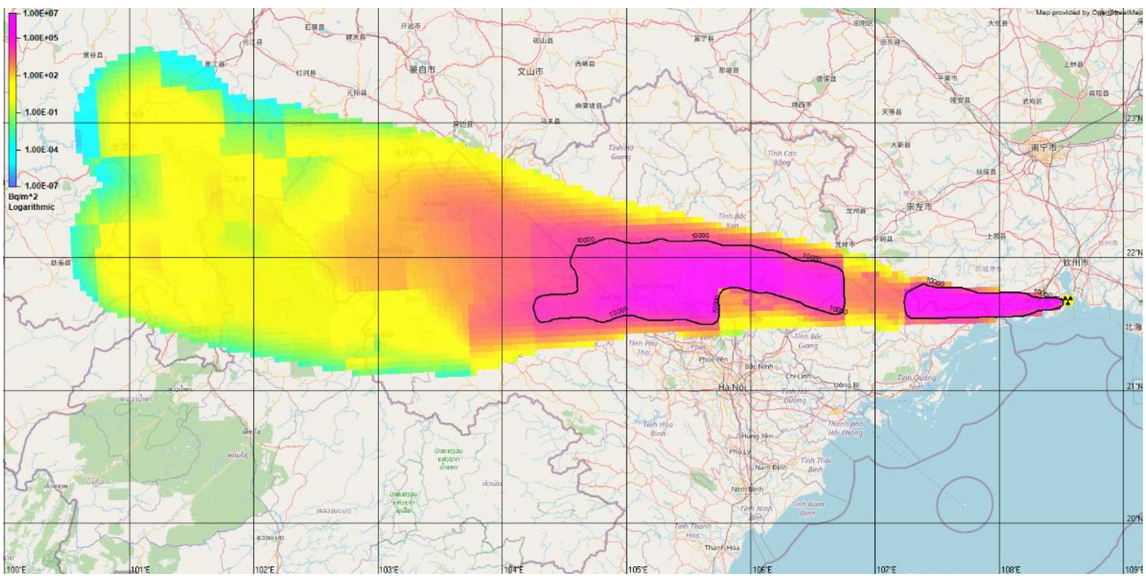

Fig. 5. Distribution of the deposition of I-131 from the first accident scenario

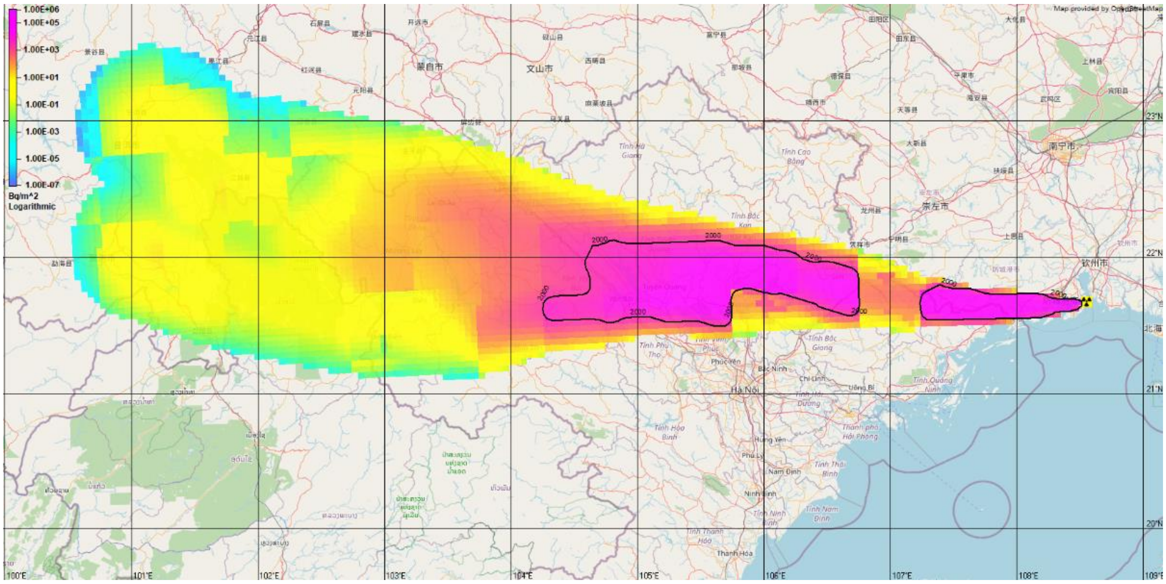

Fig. 6. Distribution of the deposition of Cs-137 from the first accident scenario

The distribution of the total dose rate caused by radionuclides is quite concentrated. The highest value of the total dose rate caused by radionuclides is 16.5 µSv/h. Most of the total dose rates are greater than 1 µSv/h (Figure 7).

After 18 hours, the radioactive plume covered part of the provinces: Quang Ninh, Lang Son, Bac Giang, Thai Nguyen, Bac Can, Vinh Phuc, Phu Tho, Tuyen Quang, Yen Bai, Lao Cai, Lai Chau, Son La, and Dien Bien. The highest total dose rate was 4.32 µSv/h (Figure 8).

After 23 hours, the radioactive plume went out of Viet Nam. The total dose rate distribution was shown in Figure 9, with the highest dose rate being 3.03 µSv/h.

In the first accident scenario, the radioactive plume traveled across Viet Nam for about 24 hours (from 3 hours to 26 hours from the time of the accident at the NPP). The highest total effective dose might occur to people in the following provinces: Quang Ninh, Lang Son, Bac Giang, Thai Nguyen, Bac Can, Vinh Phuc, Phu Tho, Tuyen Quang, Yen Bai, Lao Cai, Lai Chau, Son La, and Dien Bien. During the period of accident they were 0.12 mSv, 0.013 mSv, 0.001 mSv, 0.027 mSv, 0.006 mSv, 0.001 mSv, 0.007 mSv, 0.003mSv, 0.004 mSv, 0.001 mSv, 0.005 mSv, 0.001mSv and 0.003 mSv, respectively. Thus, during the accident, the total effective dose to the public is less than 5 mSv. With this dose, most of the interventions actions specified in Circular 25/2014/TT-BKHCN did not need to be implemented [11].

After 30 days, the highest dose rate in the region decreased to 0.7 µSv/h, the region with a dose rate greater than 1 µSv/h was all in China (Figure 10).

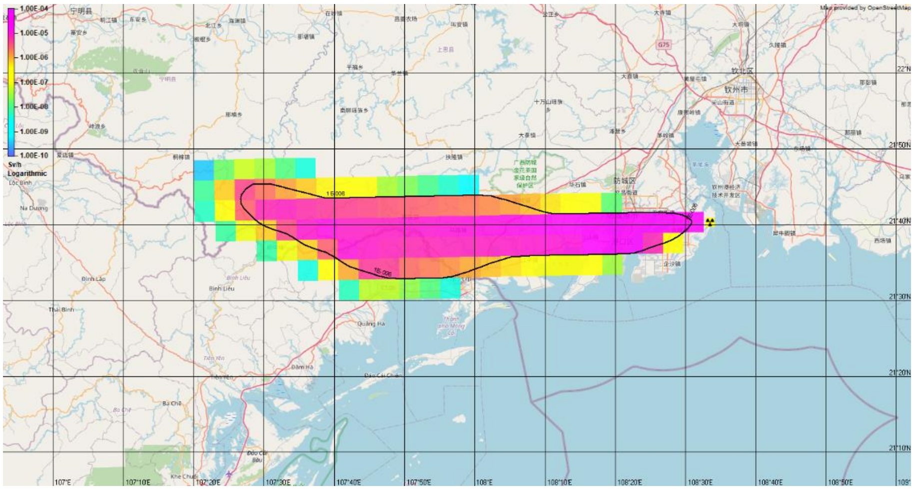

Fig. 7. Distribution of total dose rate after 3h from the first accident scenario

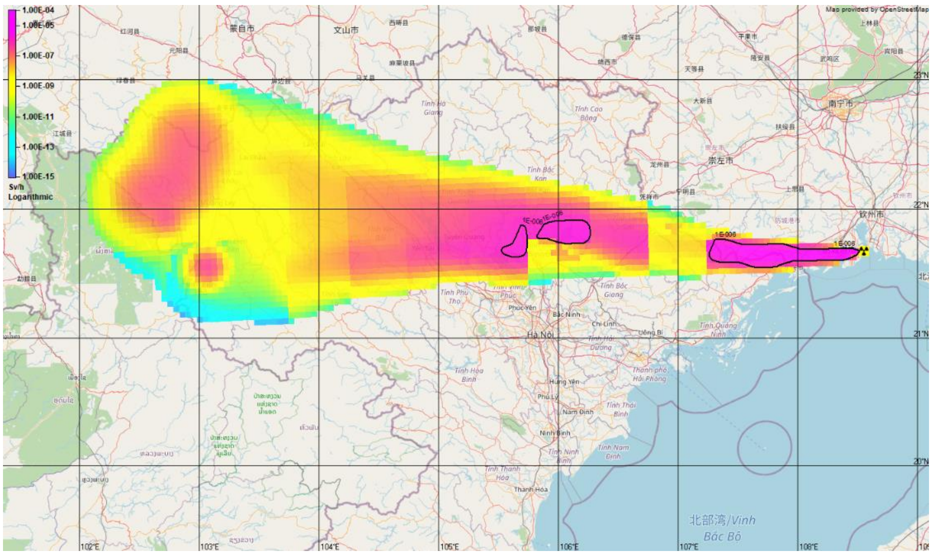

Fig. 8. Distribution of total dose rate after 18h from the first accident scenario

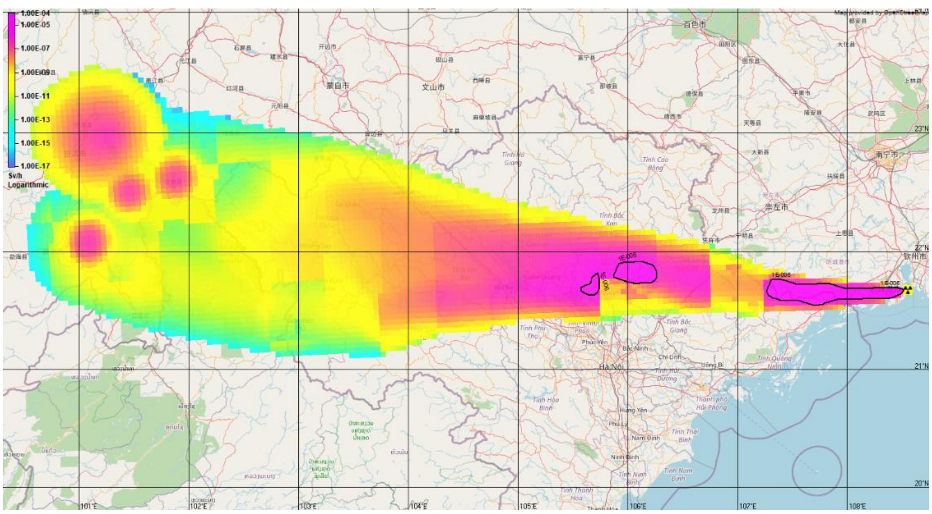

Fig. 9. Distribution of total dose rate after 23h from the first accident scenario

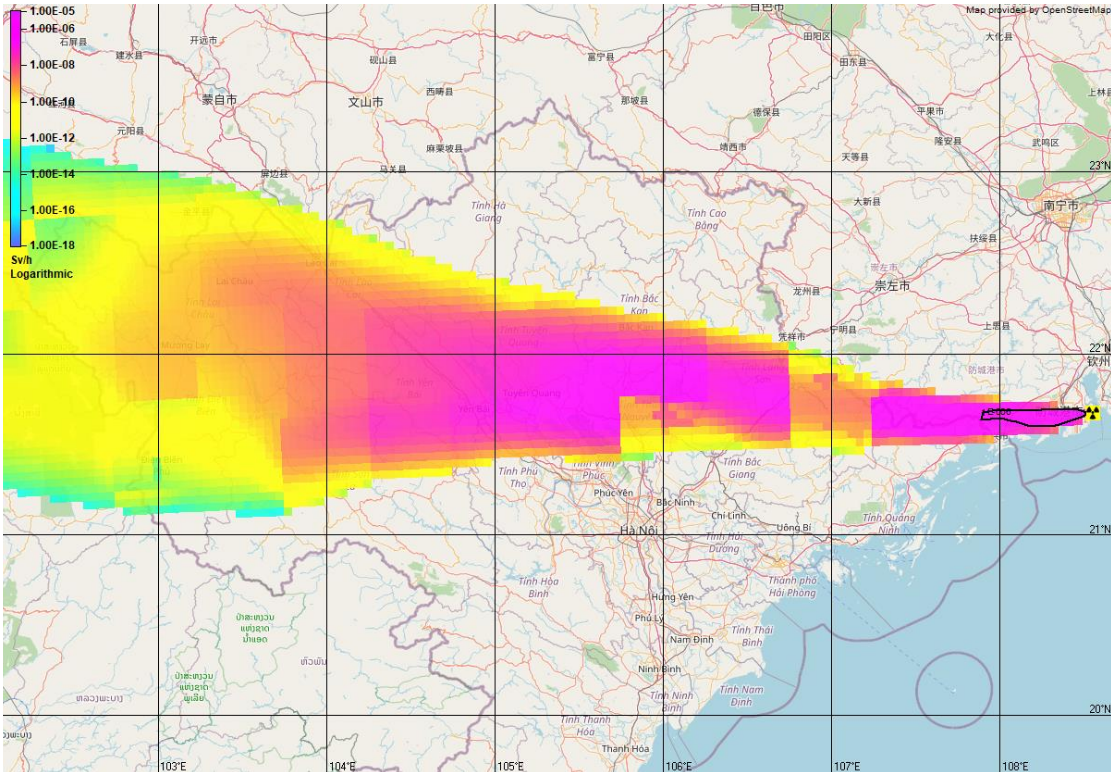

Fig. 10. Distribution of total dose rate after 30 days from the first accident scenario

B. Second Accident Scenario

The second accident scenario is a hypothetical accident that occurred at Fangchenggang NPP at 8:00 am (UTC) on March 1, 2021, with an emission time of 2 hours.

After 18 hours, the radioactive plume emitted from the Fangchenggang power plant reached Ha Tinh and Quang Binh provinces. The highest activity concentration of I-131 was 1000 Bq/m^3 (Figure 11). The plume of Cs-137 is similar to that of I-131, and the highest value was 191 Bq/m^3 (Figure 12).

After 26 hours, the radioactive plume moved northwest to Hanoi and some provinces, including Hai Phong, Thai Binh, Nam Dinh, Ninh Binh, Thanh Hoa, Nghe An, Ha Tinh, and Quang Binh. The activity concentration of I-131 is shown in Figure 13. The highest activity concentration of I-131 was 636 Bq/m^3 in Nghe An province. The activity concentration distribution of Cs-137 was similar to that of I-131 (Figure 14), with the highest value of 89.4 Bq/m^3.

After 48 hours, the radioactive plume went out of Viet Nam, and the center of the radioactive plume has covered almost all of the northern and central provinces from Thanh Hoa to Quang Binh. The activity concentration distribution of I-131 is shown in Figure 15. The highest activity concentration of I-131 was 31.2 Bq/m^3. The activity concentration distribution of Cs-137 was similar to that of I-131 (Figure 16), with the highest value of 7.53 Bq/m^3.

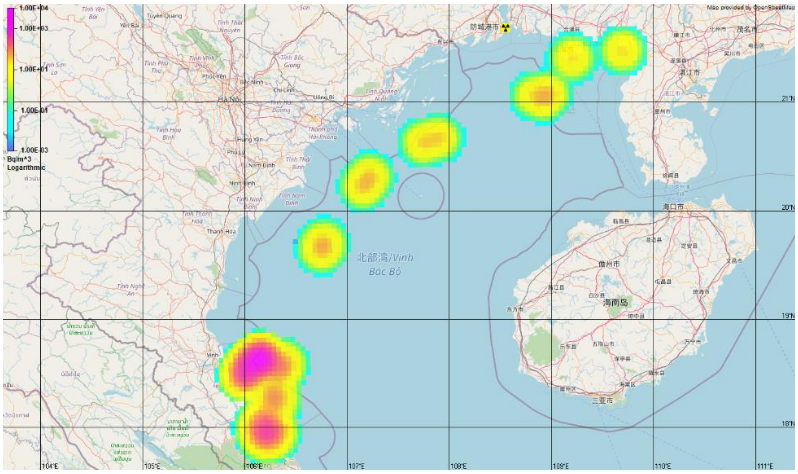

Fig. 11. Distribution of the activity concentration of I-131 after 18h from the second accident scenario

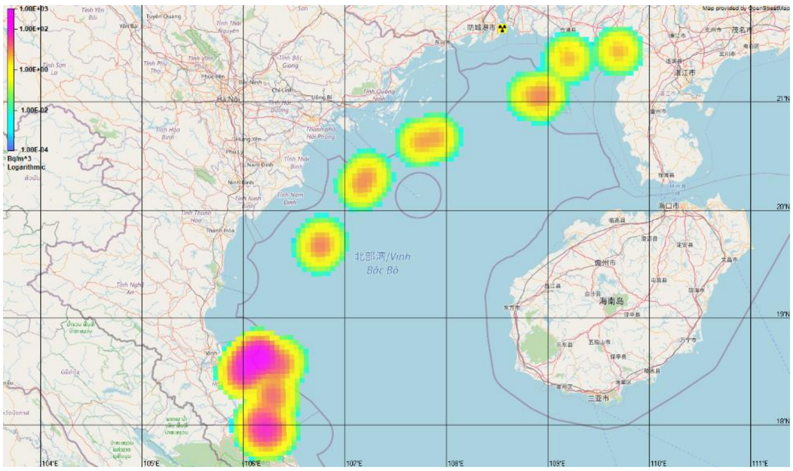

Fig. 12. Distribution of the activity concentration of Cs-137 after 18h from the second accident scenario

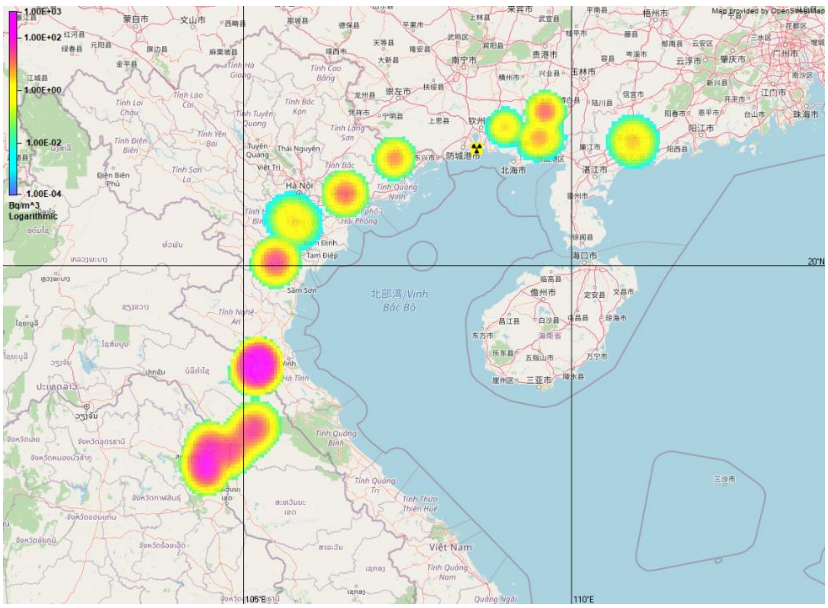

Fig. 13. Distribution of the activity concentration of I-131 after 26h from the second accident scenario

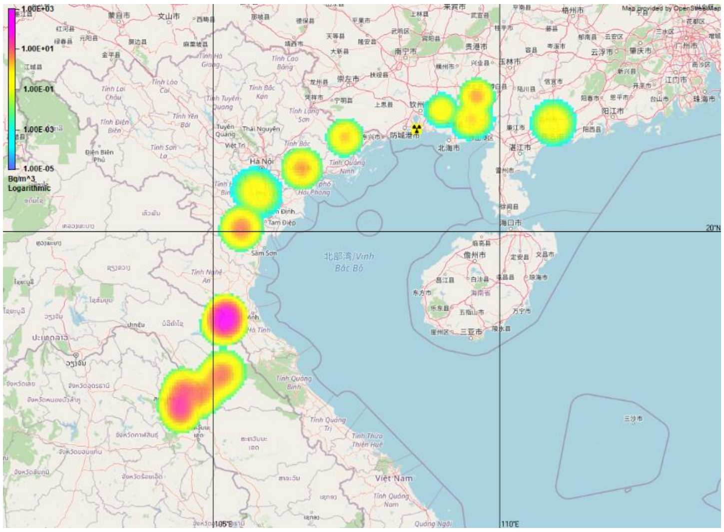

Fig. 14. Distribution of the activity concentration of Cs-137 after 26h from the second accident scenario

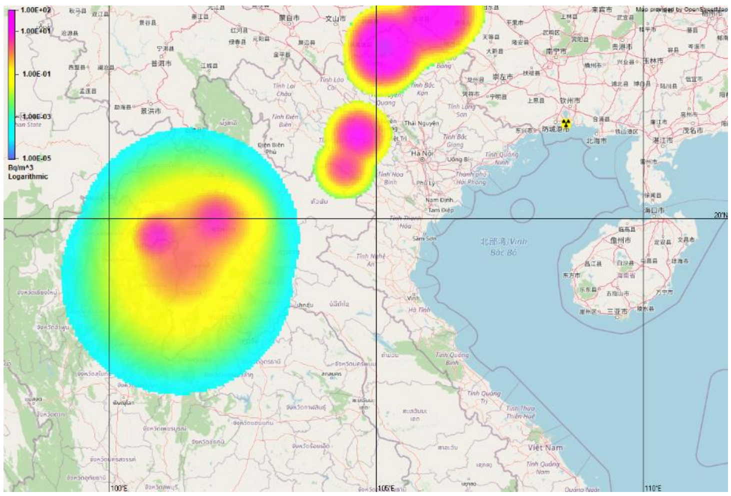

Fig. 15. Distribution of the activity concentration of I-131 after 48h from the second accident scenario

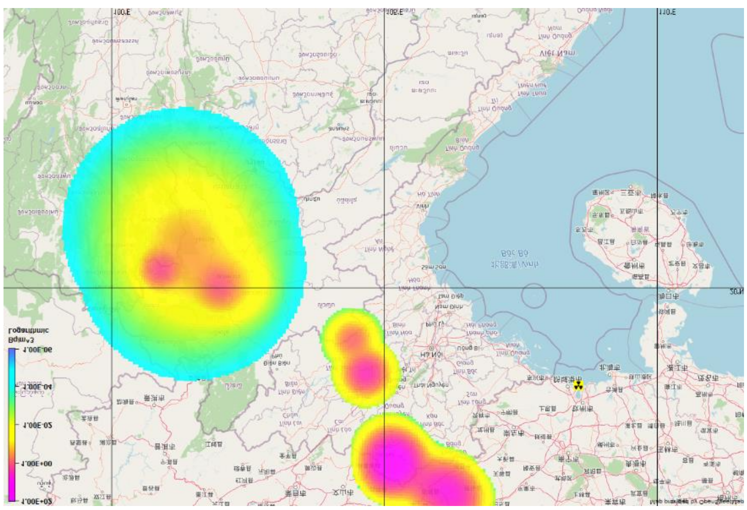

Fig. 16. Distribution of the activity concentration of Cs-137 after 48h from the second accident scenario

The deposition distribution of I-131 and Cs-137 after 48h is shown in Figure 17 and Figure 18. The highest I-131 and Cs-137 depositions in Viet Nam are 6010 Bq/m^2 and 4920 Bq/m^2, respectively. Therefore, with the area where the deposition of I-131 is greater than 10 kBq/m^2 and the deposition of Cs-137 is greater than 2 kBq/m^2, local food consumption should be immediately stopped until the analysis results of radionuclides I-131, and Cs-137 are available to verify whether the activities of Cs-137 and I-131 in food exceed the allowable limits or not [11].

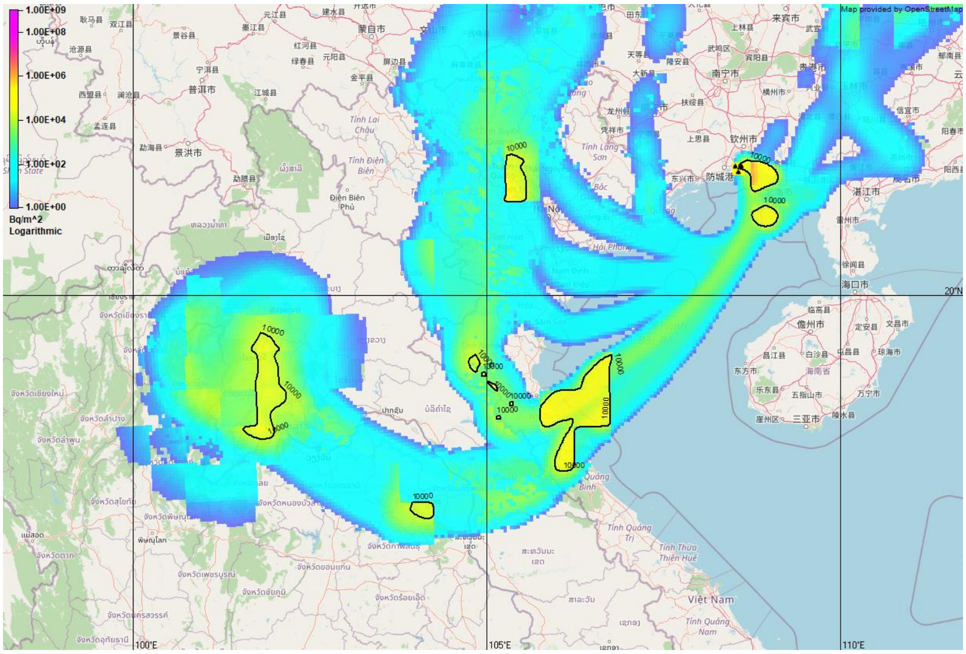

Fig. 17. Distribution of the deposition of I-131 and Cs-137 from the second accident scenario

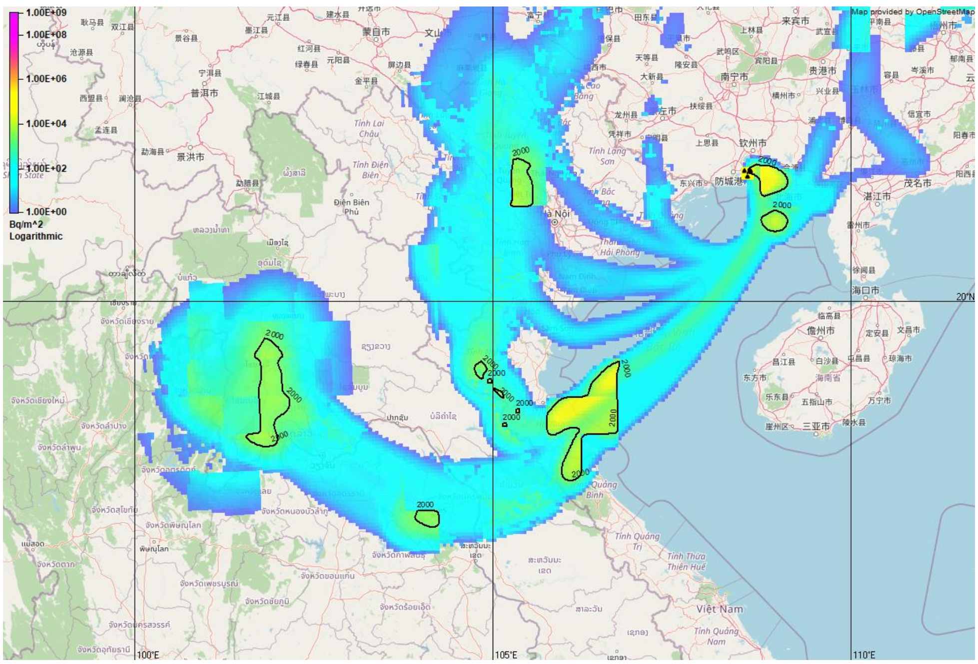

Fig. 18. Distribution of the deposition of I-131 and Cs-137 from the second accident scenario

The distribution of the total dose rate caused by radionuclides is quite concentrated. Although the highest value of total dose rate caused by radionuclides reached 1.54 µSv/h, the area with a dose rate greater than 1 µSv/h is relatively small, mainly located in the East Sea (Figure 19).

The distribution of the total dose rate after 26 hours is shown in Figure 20. The highest value of the total dose rate is 1.26 µSv/h. The area with a dose rate greater than 1 µSv/h is quite small, mainly located in the East Sea.

After 48 hours, most of the radioactive plumes had gone outside Viet Nam. The total dose rate distribution is shown in Figure 21. The area on land and sea of Viet Nam has a total dose rate of less than 1 µSv/h.

In the second accident scenario, the radioactive plume traveled across Viet Nam for about 48 hours (from 18 hours to 55 hours from the time of the accident at the NPP). The highest total effective dose may occur to people in the following provinces: Quang Binh, Ha Tinh, Nghe An, and Thanh Hoa. During the period of accident they were 0.015 mSv, 0.026 mSv, 0.04 mSv, 0.002 mSv, respectively. Thus, during the accident, the total effective dose to the public is less than 5 mSv. With these dose levels, most of the intervention actions specified in Circular 25/2014/TT-BKHCN need not be implemented [11].

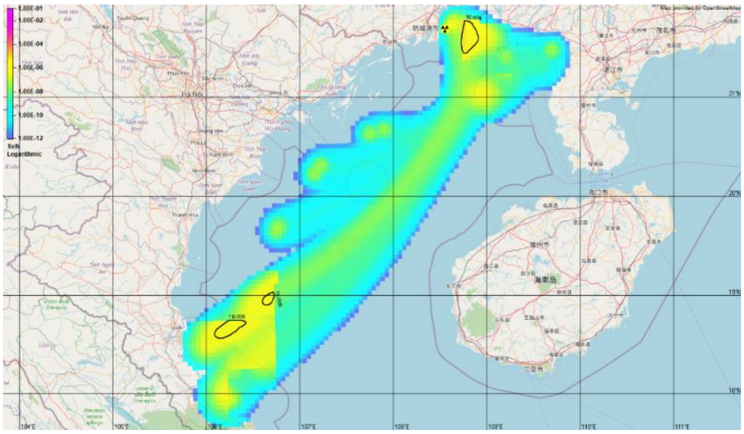

Fig. 19. Distribution of total dose rate from the second accident scenario

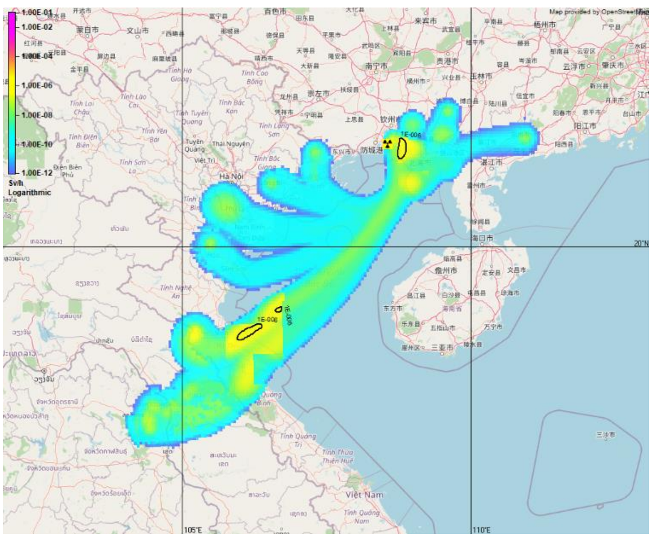

Fig. 20. Distribution of total dose rate from the second accident scenario

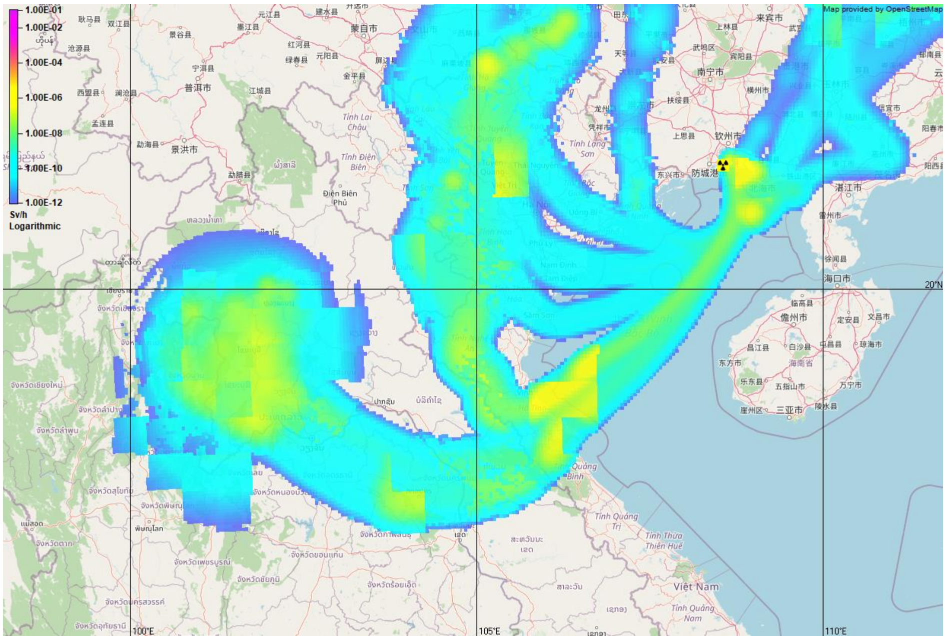

Fig. 21. Distribution of total dose rate from the second accident scenario

IV. CONCLUSIONS

In this study, we have achieved the initial goal: to assess the possibility of radioactive material released from Fangchenggang NPP into Viet Nam with a level 6 accident scenario of the INES scale with extreme meteorological conditions. Furthermore, the impact of radioactive material released from Fangchenggang NPP on humans and the environment has been evaluated, and responding solutions have been proposed for the corresponding accident scenarios.

Based on the radioactive dispersion simulation and total effective dose distribution of emergencies originating from Fangchenggang NPP, no intervention level for emergency protective actions and relocation and relocation termination actions are exceeded; therefore, no corresponding intervention action needs to be done. However, several operational intervention levels based on measurable parameters such as dose rate and deposition density of radionuclides on the ground surface have been exceeded.

The simulation results show that the radioactive plume affecting Viet Nam has a relatively wide area, possibly including all of the northern provinces and some central provinces.

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