Study on the Atmospheric Release of Radioactive Materials in Small modular reactor (SMR) Accidents in Thailand

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Abstract:

This study aims to evaluate and analyze the dispersion of radioactive substances in the atmosphere resulting from nuclear accidents using advanced computer simulations. The main objective is to utilize this knowledge for academic advancements and inform strategic planning for managing severe accidents at nuclear power plants in Thailand and ASEAN. The focus of the study is on the emergency planning zone for a Small Modular Reactor (SMR) power plant in Thailand, specifically examining two distinct sites: one in the south and another in the northeast. Hypothetical accident scenarios for the SMR-iPWR type in cases of Station Blackout (SBO) are carefully aligned with diverse weather conditions corresponding to different seasons. To conduct the simulations, the study employs JRODOS, a simulation tool, to predict the atmospheric dispersion of Cs-137 and I-131. The assessment primarily focuses on the Total Effective Dose Equivalent (TEDE) values during the critical 7-day period following an accident. These simulation outcomes play a crucial role in contributing to the risk assessment and decision-making processes associated with nuclear installation and site selection. The results of the study indicate that the area impacted by accidents in the case of the SMR-iPWR type is significantly smaller compared to conventional reactors. This finding positions SMR technology as a potential new option for energy, considering its reduced impact in the event of accidents.

Keywords: Small modular reactor, SMR, Atmospheric release, Dispersion, Emergency, ASEAN NPSR

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1. INTRODUCTION

Small Modular Reactors (SMRs) have gathered significant interest globally due to their potential to offer more flexible, cost-effective, and safer nuclear power solutions, contributing to a sustainable and secure energy future. The U.S. Department of Energy (DOE) has been actively supporting the development and deployment of SMRs, with companies like NuScale Power making significant progress [1]. The UK has shown strong interest in SMRs as part of its strategy to decarbonize its energy sector and ensure energy security [2]. Canada is exploring SMRs for both domestic use and as an export opportunity, particularly for remote and indigenous communities [3]. In Asia, China [4], South Korea [5, 6], and Japan [7, 8], are investing in SMR technology to enhance their energy mix and reduce emissions. Argentina, developing country, is actively developing SMR technology, with the CAREM reactor being a notable project aimed at both domestic use and export [9].

SMRs are an attractive option for enhancing energy security and addressing economic challenges faced by developing countries. However, several issues have arisen as challenges and considerations. Developing and harmonizing regulatory frameworks for SMRs is crucial to ensure their safe deployment and operation. Gaining public trust and acceptance of nuclear technology remains a significant challenge. Thailand and ASEAN countries have shown interest in these new power solutions. This study focused on the emergency planning zone for an SMR power plant in Thailand, specifically examining two distinct sites: one in the south and another in the northeast. Hypothetical accident scenarios for the SMR-iPWR type were analyzed. The Java-based Real-time On-line Decision Support System (JRODOS) [10] was used as a simulation tool to predict nuclear consequences due to the atmospheric dispersion of Cs-137 and I-131 in the selected area. These results play a crucial role in contributing to the risk assessment and decision-making processes associated with nuclear installation and site selection.

2. METHODOLOGY

2.1. Source Term

Station Black-Out (SBO), hypothetical accident scenarios of the SMR Thailand case study was selected based on the potential accident with early containment failures having a large uncertainty of source term release into the environment. The source term release of the SBO accident scenario was simulated by MAAP5.05 [11, 12]. Generic iPWR conceptual design and the thermal-hydraulic performance analysis of the 300 MW iPWR in this SMR study were assumed to be an integral-type, natural-circulation driven, and small LWR based on the proposed iPWR. The in-core components were assumed to be nearly similar to contemporary PWRs simulation [13], and generic iPWR thermal–hydraulic parameters and design were used in the source term release simulation [1, 5, 14, 15]. The source term for a conventional nuclear power plant (NPP) was calculated using the Optimized Power Reactor 1000 (OPR-1000), a pressurized water reactor (PWR) with an electrical output of 1,000 megawatts (MWe). I-131 and Cs-137 were selected from the nuclide release calculation as the nuclides of interest for the atmospheric dispersion study, with I-131 being used to study short-term consequences and Cs-137 for long-term consequences.

2.2. Site Selection

For site selection in the nuclear consequence analysis of the SMR case study in Thailand, the authors considered five candidate locations based on past feasibility studies of nuclear power programs. Ubon Ratchathani, a province in the north-eastern region, was identified as the most suitable site for considering the emergency planning zone due to its proximity to the Laos and Cambodia borders [16]. The other site is Suratthani province, located in the southern part of the country.

2.3. Meteorological Data

The main winds affecting Thailand are primarily influenced by the monsoon system, leading to three distinct seasonal wind patterns: (1) Southwest monsoon winds (Rainy Season - June to October) bringing heavy rains during the rainy season with moderate to strong wind speed; (2) Northeast monsoon winds (Cool Season - November to February) blow from the Northeast direction, leading to cooler and drier air from the Asian continent, results in lower temperatures and reduced rainfall, particularly in northern and northeastern Thailand. Winds are generally lighter compared to the southwest monsoon; and (3) Local winds and seasonal variations (Hot Season from March to May) the winds are generally light to moderate with various directions often from the south or southeast, contributing to the hot and dry conditions prevalent during this period.

In this study, the selected meteorological data from each season were used to represent the cases affecting radioactive atmospheric dispersion. The meteorological data from the National Oceanic and Atmospheric Administration (NOAA) [17] were explored from years 2020 - 2023. Thailand experienced its most turbulent weather during the monsoon season, particularly from May to October. This period is characterized by heavy rains, strong winds, and occasional tropical storms, leading to significant disruptions and hazards.

2.4. Emergency Planning Zones

The radioactive plume dispersion and near-ground air concentrations of the nuclides of interest were simulated for a 7-day prognosis after the accident using JRODOS to identify the areas impacted by the radiological incident. The Total Effective Dose Equivalent (TEDE) during that period was also calculated and then compared with the Protective Action Levels (PALs) for the SMR site to assess mitigation strategies for the public, as recommended by the Canadian Nuclear Safety Commission (CNSC) and the United States Nuclear Regulatory Commission (U.S. NRC) [13, 18, 19]. These dose levels in PALs were used to inform the size requirements for emergency planning zones around NPPs. Fig. 1 shows the dose levels in PALs for emergency planning around the general NPPs [13].

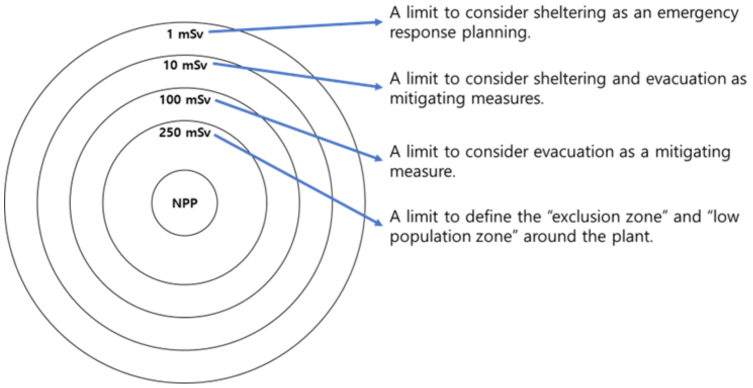
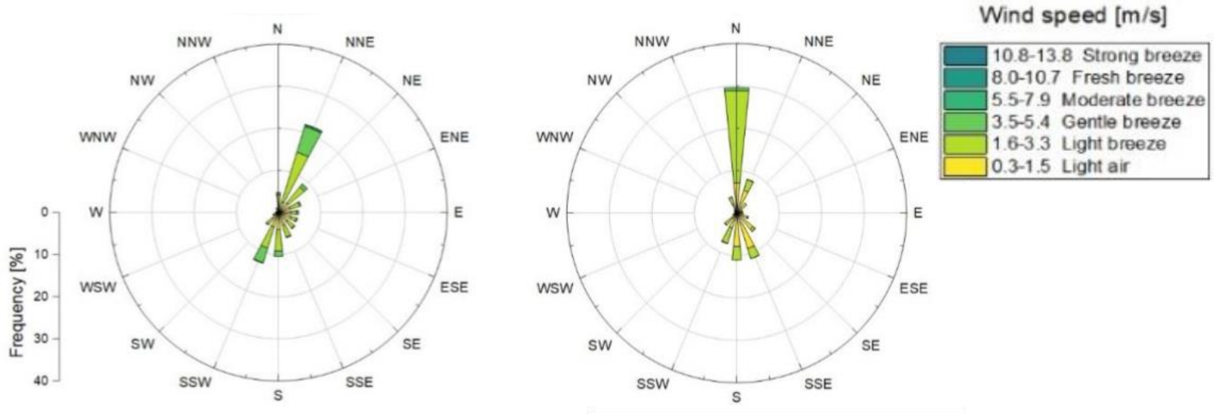


Figure 1. Dose levels for emergency planning zones around the general NPPs [13].

3. RESULTS AND DISCUSSION

3.1. Meteorological Data Analysis

The study on the changes in weather conditions at two locations was conducted by analyzing the frequency distribution of hourly climate data through the years from 2020 to 2023. The results are shown in Figures 2 – 4, with plot (a) for Ubon Ratchathani and plot (b) for Suratthani.

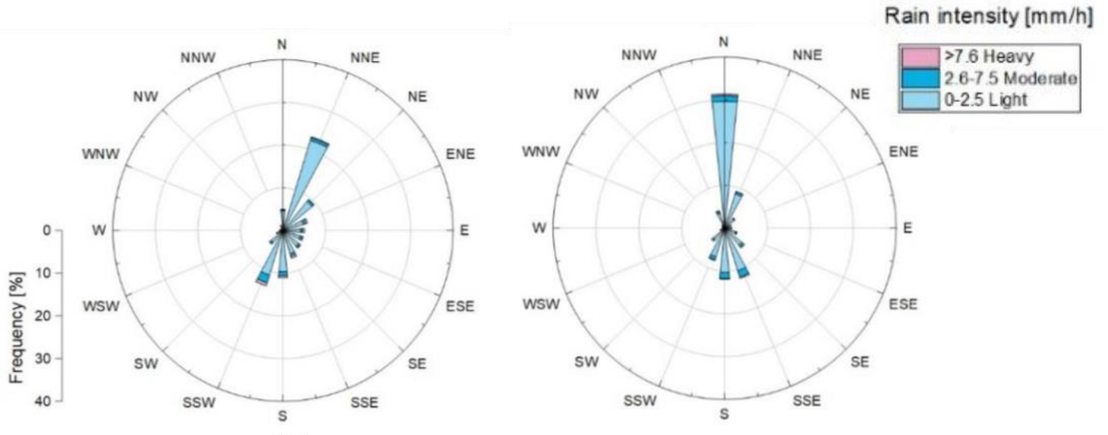


(a) (b)

Figure 2. Wind data for each location: (a) Ubon Ratchathani and (b) Suratthani.

Figure 2 shows the frequency distribution of wind data at the two locations, indicating different wind patterns at each site. In plot (a), the primary wind directions were from the north-northeast (NNE) and south-southwest (SSW), with a fairly balanced wind distribution between these directions. The wind speeds mostly fall within the gentle breeze range (3.5–5.4 m/s) and light breeze range (1.6–3.3 m/s). In plot (b), the highest frequency of wind speeds was from the north (N), with a noticeable concentration of light breeze (1.6–3.3 m/s) and a stronger concentration from the north.

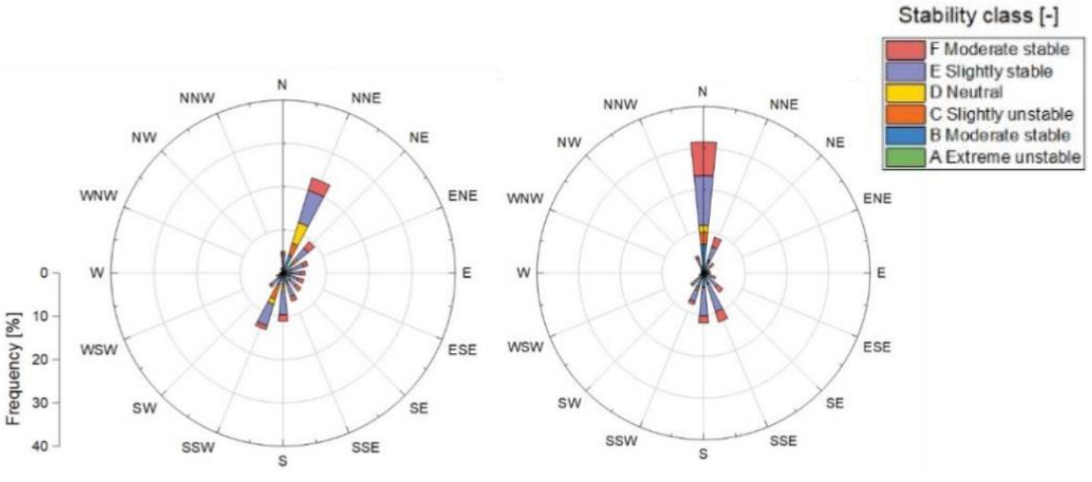
Figure 3 provides the information on the frequency distribution of rainfall at the two locations. The data indicated that the rainfall density was in the light to Moderate rain range, with over 50% being light rain, confirming low rainfall amounts at all locations. The most frequent and intense rainfall occurs from the north and south directions, with a higher concentration of moderate to heavy rainfall in the south-southwest (SSW) for Ubon Ratchathani (Figure 3a) and in the north (N) for Suratthani (Figure 3b).



(a) (b)

Figure 3. Rain intensity for each location: (a) Ubon Ratchathani and (b) Suratthani.

Figure 4 shows the frequency distribution of atmospheric stability at the two selected locations. The majority of the atmospheric stability levels were slightly stable (E) to moderate stable (F), indicating high stability suitable for the dispersion of radioactive substances. Both plots show rather similar weather conditions, but with slight variations in the directionality of these conditions. Plot (a) shows a higher frequency of slightly stable (E) conditions in the north-northeast (NNE) direction, while plot (b) features with a higher frequency of moderately stable (F) conditions in the north (N).



(a) (b)

Figure 4. Stability class for each location: (a) Ubon Ratchathani and (b) Suratthani.

Representative meteorological data that used in the calculation were selected to cover all weather conditions throughout the year, including extreme wind speeds and extreme stability classes, in order to study the behaviours of the source term releases of Cs-137 and I-131 in a conservative aspect.

The selected weather data for this study are (1) January for Cool Season where the predominant wind is from the Northeast monsoon winds, (2) April for Hot Season to show the impact from where the Local winds and seasonal variation, (3) June and (4) October for Southwest monsoon winds (Rainy Season) with June standing out as the peak of turbulence in year 2023.

3.2. Atmospheric dispersion simulations

The maximum releases of Cs-137 and I-131 were used to estimate the nuclear consequences of the iPWR, forming a major part of the emergency response and Protective Action Levels (PAL) zones planning. The highest source term values of Cs-137 and I-131 from each type of the reactors were used as inputs for atmospheric dispersion simulations using the JRODOS program as listed in Table 1.

Table 1: The source term for atmospheric calculation

	I-131 (TBq)	Cs-137 (TBq)
Conventional reactor	26029.050	6096.020
SMR	111.709	9.685

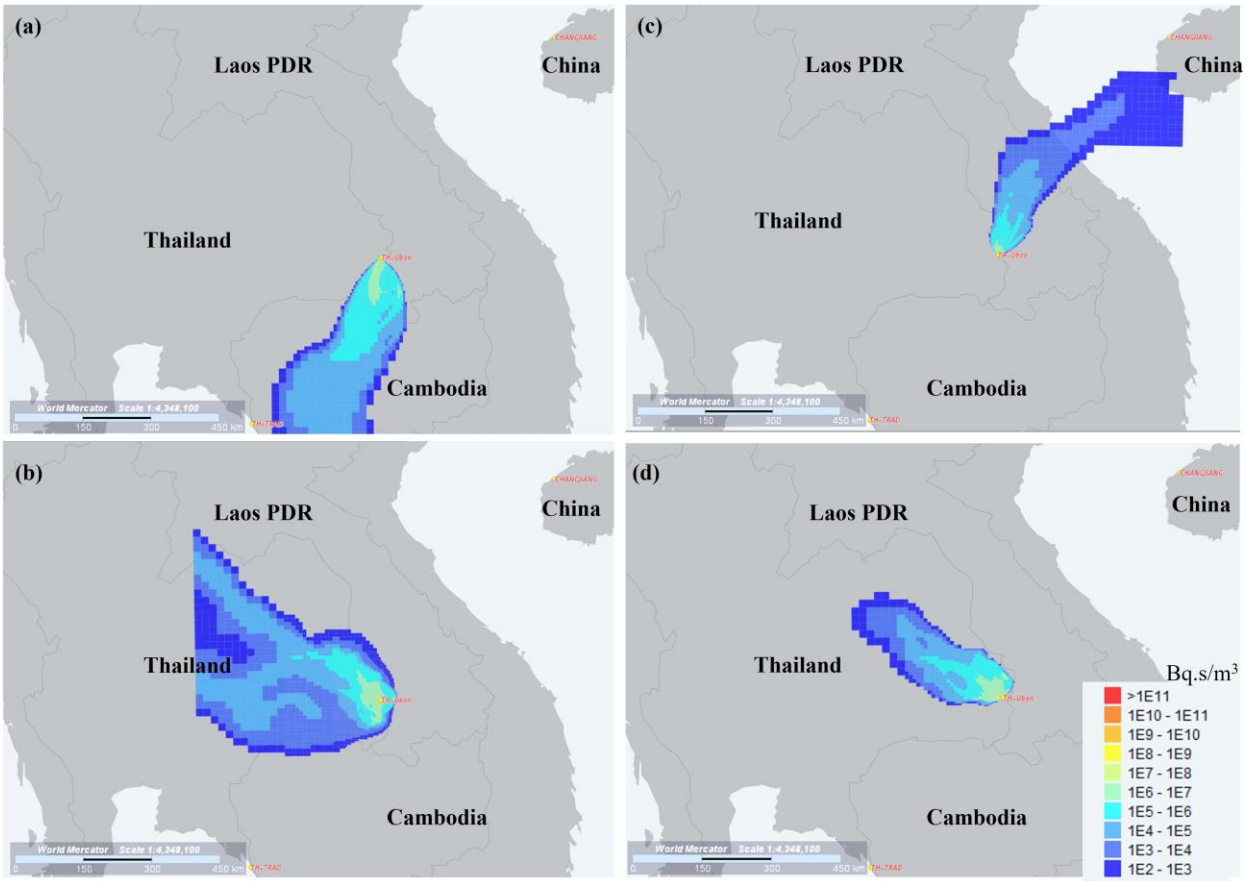


Figure 5. The near-ground air concentrations of I-131 releases at Ubon Ratchathani in different weather conditions: (a) January – Cool Season; (b) April – Hot Season; (c) June – Monsoon Season (Turbulent); and (d) October – Monsoon Season.

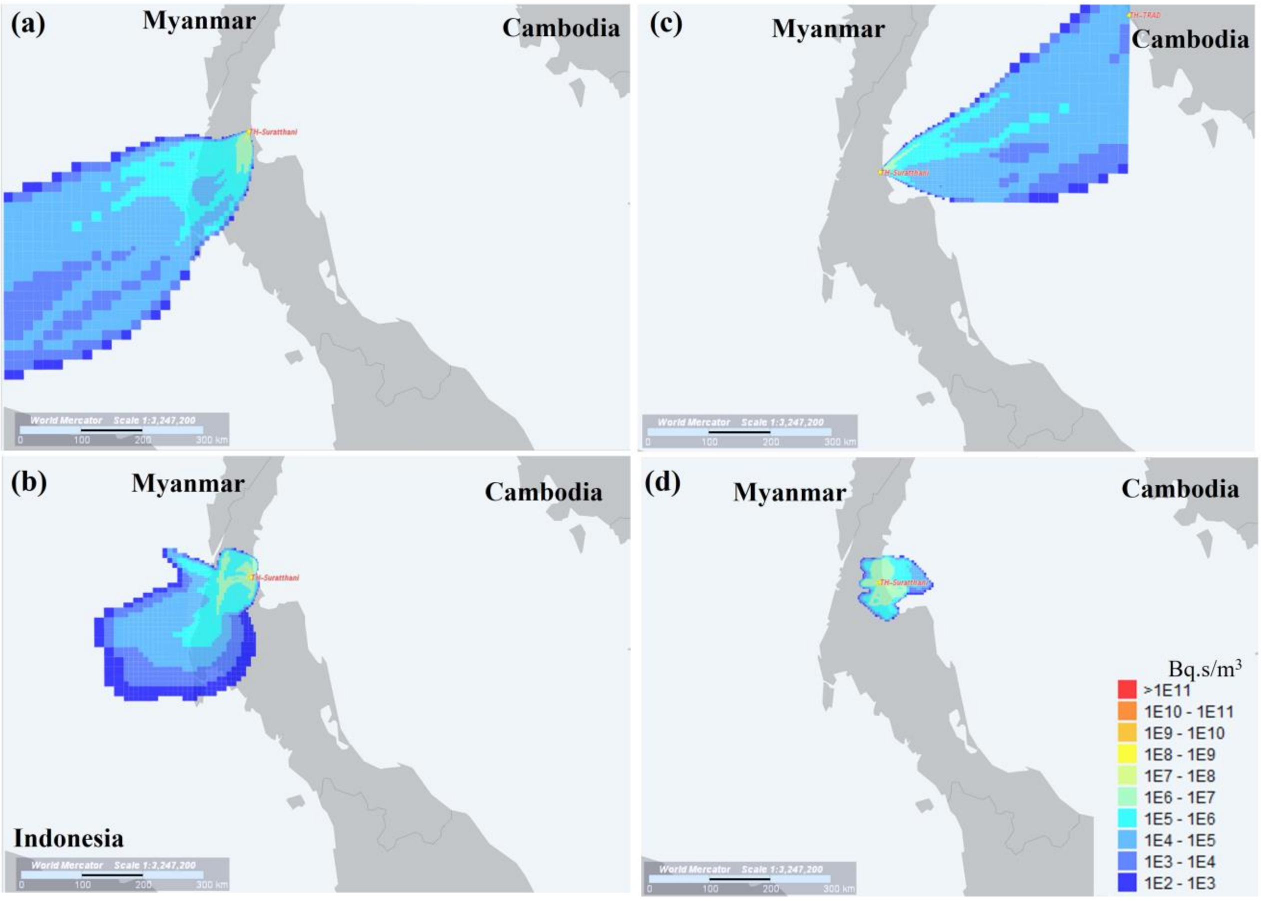


Figure 6. The near-ground air concentrations of I-131 releases at Suratthani in different weather conditions: (a) January – Cool Season; (b) April – Hot Season; (c) June – Monsoon Season (Turbulent); and (d) October – Monsoon Season.

Figure 5 and 6 illustrate the near-ground air concentrations of I-131 releases from an SMR located in Ubon Ratchathani and Suratthani, Thailand, during different seasons of the year. Each subfigure represents a different season and shows the geographic dispersion of I-131 releases. During Cool Season, the dispersion is predominantly towards the southwest, affecting parts of Laos PDR and Cambodia for the Ubon Ratchathani case, and extending towards Indonesia for the Suratthani case. In the period of Hot Season, the plume disperses slightly differently compared to January. It moves towards the west, extending in both north and south directions, but with a broader impact area, covering more of Thailand. This suggests higher dispersion due to potentially stronger winds or different atmospheric conditions. For Monsoon Season during the peak of turbulence in June, the plume is more extensive towards the northeast, significantly affecting Laos PDR and reaching into parts of China for the Ubon Ratchathani case, while it touches the border of Cambodia for the Suratthani case. The turbulent monsoon conditions likely contribute to a wider and more erratic dispersion pattern. Whereas in October, the plume is more localized compared to June, extending towards the southeast and mainly affecting parts of Thailand. The dispersion is more confined, indicating potentially less turbulent conditions than in June. The dispersions for the conventional reactor resulted in a similar dispersion trend but with significantly higher activity concentrations of the radionuclides of interest, by 2 to 3 orders of magnitude. These seasonal variations are crucial for emergency planning and risk assessment, as they highlight the importance of considering different meteorological conditions in the event of a nuclear release.

3.3. Emergency planning zones

Figure 7 illustrates the Total Effective Dose Equivalent (TEDE) of nuclear consequences occurring in the hot season (April) for the Suratthani site, along with the size requirements for the SMR emergency planning zones. When comparing the emergency planning zones with TEDE dose levels against the PALs criteria in Figure 1, it was found that the TEDEs from nuclear consequences were very small. The maximum TEDEs within the SMR emergency planning zones were limited to 1 mSv, necessitating emergency response planning for sheltering within a radius of less than 5 km.

Figure 8 presents the TEDE of nuclear consequences in Suratthani for the same season as in Figure 7 and the size requirements for conventional NPP emergency planning zones. The same methods were applied to investigate the nuclear consequences of the SBO case in a conventional NPP using the OPR-1000 reactor type. When comparing the nuclear consequences of large NPPs in Figure 8 with those of SMRs in Figure 7, it was found that the radioactive consequences for SMRs, with TEDEs of less than 1 mSv, are confined within Thailand, with no cross-border impacts on neighboring ASEAN countries. In contrast, the radioactive consequences of conventional NPPs could potentially affect neighboring ASEAN countries such as Laos and Cambodia, and possibly China in the case of Ubon Ratchathani, as well as Malaysia, Indonesia, and Myanmar in the case of Suratthani. The estimated maximum distances (measured as a radius) from the center of the SBO accident where the radiation dose exceeds 1 mSv for all cases are summarized in Table 2.

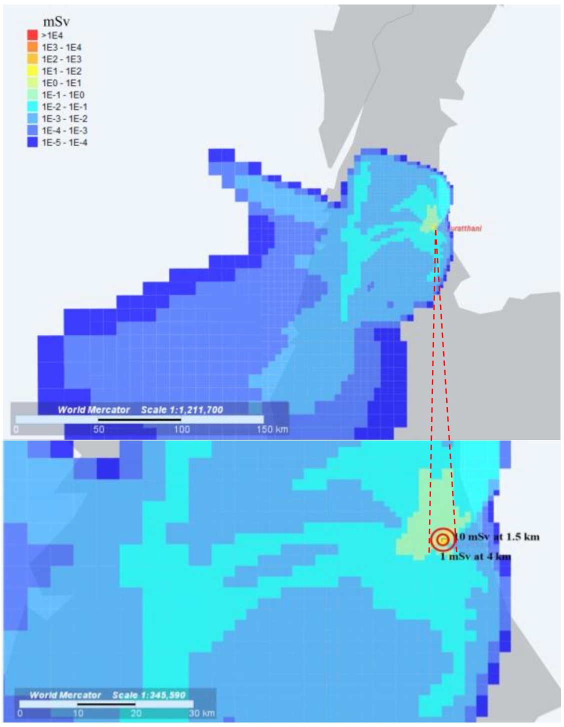


Figure 7. TEDE of nuclear consequences in hot season (April) and size requirements for the SMR emergency planning zones.

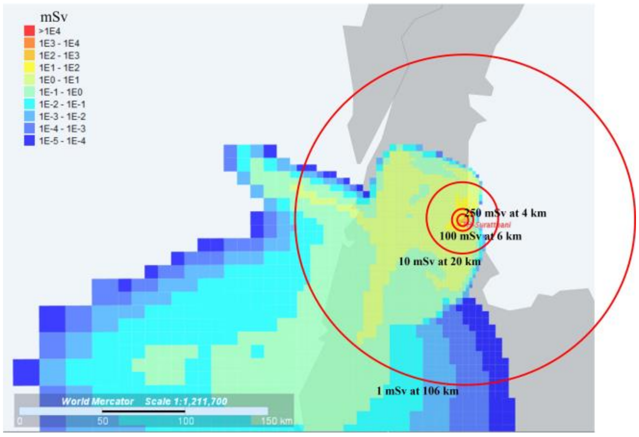


Figure 8. TEDE of nuclear consequences in hot season (April) and size requirements for the conventional NPP emergency planning zones.

Table 2: Approximate radius exceeding 1-mSv dose level in an SBO accident

Site	Approximate maximum radius exceeding 1-mSv dose level in an SBO Accident (km)			
	Cool Season	Hot Season	Monsoon Season (Turbulent)	Monsoon Season
Ubon Ratchathani				
- SMR	6	6	4	8
- Conventional NPP	135	125	55	130
Suratthani				
- SMR	4	4	4	4
- Conventional NPP	140	106	135	50

The Table 2 compares the approximate maximum radius (in kilometers) exceeding a 1-mSv dose level during an SBO accident for two different reactor types, SMR and conventional NPP, across different seasons at Ubon Ratchathani and Suratthani. The radius exceeding 1 mSv is significantly larger for conventional NPPs compared to SMRs. In Ubon Ratchathani, the radius for conventional NPPs ranges from 55 km to 135 km depending on the season, while for SMRs, it ranges from 4 km to 8 km. In Suratthani, the radius for conventional NPPs varies from 50 km to 140 km, whereas it remains consistent at 4 km for SMRs across all seasons.

Hence, according to this comparison, SMRs are potential reactors to support low nuclear consequences in remote areas with flexible emergency planning zones for sheltering and evacuation. Moreover, SMRs are important technology to reduce conflicts between neighboring countries regarding radioactive transboundary issues, as the impact regulations of limited dose exposure may vary from country to country, particularly where SMR reactors are operated.

4. CONCLUSION

Interest in SMR technology is growing in newcomer countries such as Thailand and other ASEAN countries. Understanding the risks of source term release and dose exposure from SMRs to people and the environment is crucial for emergency preparedness and response. This study extends the application of atmospheric dispersion of radioactive releases to inform strategic planning for nuclear consequences and determine the size requirements for SMR emergency planning zones. The case study focuses on the SBO accident scenario of an iPWR located in Ubon Ratchathani (Northeast) and Suratthani (South) provinces of Thailand.

The source term release was used to estimate consequences for determining major emergency response plans. The maximum releases of Cs-137 and I-131 were set as input for the JRODOS program for radioactive consequence analysis and emergency planning zone investigation. The maximum TEDE was limited to 1 mSv, allowing local governments to evacuate people within a small area (less than 5 km radius) to avoid dose exposure. Comparisons of nuclear consequences between SMRs and conventional NPPs in the same accident scenarios showed that SMRs require smaller emergency planning zones (only a 1 mSv zone) and do not result in significant dose exposure across ASEAN neighboring countries.

In conclusion, the study highlights the potential of SMR technology to support flexible emergency planning zones for sheltering and evacuation, minimizing significant dose exposure to neighboring countries. This underscores the viability of SMRs as a safer and more manageable nuclear power option for newcomer countries, particularly in regions with close international borders like ASEAN.

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References

[1] Ingersoll, D. T., Houghton, Z. J., Bromm, R., Desportes, C., 2014. NuScale small modular reactor for Co-generation of electricity and water. Desalination 340, 84-93. https://doi.org/10.1016/j.desal.2014.02.023.

[2] The Department of Energy and Climate Change, 2016, SMR Techno-Economic Assessment Project 3: SMRs Emerging Technology Assessment of Emerging SMR Technologies Summary Report, NNL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665274/TEA_Project_3_-_Assessment_of_Emerging_SMR_Technologies.pdf

[3] Hummel, D. W., Chouhan, S., Lebel, L., Morreale, A. C., 2020. Radiation dose consequences of postulated limiting accidents in small modular reactors to inform emergency planning zone size requirements. Ann. Nucl. Energy 137, 107062. https://doi.org/10.1016/j.anucene.2019.107062.

[4] Shi, X., Sun, J., Chen, Q., Wang, H., 2021. Uncertainty analysis and its application of radioactive source term of HPR1000 under severe accident. International Journal of Advanced Nuclear Reactor Design and Technology 3, 134-138, https://doi.org/10.1016/j.jandt.2021.07.004.

[5] Kim, K. M., Lee, B. I., Cho, H. H., Park, J. S., Chung Y. J., 2011. Numerical study on thermo-hydrodynamics in the reactor internals of SMART, Nucl. Eng. Des. 241(7), 2536-2543. https://doi.org/10.1016/j.nucengdes.2011.04.032.

[6] Kang, H. O., Lee, B. J., Lim, S. G., 2024. Light water SMR development status in Korea, Nucl. Eng. Des. 419, 112966. https://doi.org/10.1016/j.nucengdes.2024.112966.

[7] Tsuboi, Y., Arie, K., Ueda, N., Grenci, T., Yacout, A.M. , Design of the 4S reactor, Nucl. Technol. 178 (2) (2012) 201–217, https://doi.org/10.13182/nt10-74.

[8] International Atomic Energy Agency (IAEA), Status report- MSR-FUJI, last update july 28, 2016, Tech. Rep, International Atomic Energy Agency, Vienna, Austria, 2016, https://aris.iaea.org/PDF/MSR-FUJI.pdf.

[9] Magan, H. B., Delmastro, D. F., Markiewicz, M., Lopasso, E., Diez, F., Giménez, M., Rauschert, A., Halpert, S., Chocrón, M., Dezzutti, J. C., Pirani, H., Balbi, C., Fittipaldi, A., Schlamp, M., Murmis, G. M., Lis, H., 2011. CAREM project status, Sci. Technol. Nucl. 2011, 140373. https://doi.org/10.1155/2011/140373.

[10] Ievdin, I., Trybushnyi, D., Staudt, C., Landman. C., 2017. JRodos user guide. Karlsruher Institute of Technology, Institut für Kern- und Energietechnik, Germany. https://resy5.ites.kit.edu/JRODOS/documents/JRodos_UserGuide.pdf.

[11] Fauske & Associates LLC (FAI), 2019. Modular Accident Analysis Program 5.05 (MAAP5.05). Electric Power Research Institute, Washington D.C.

[12] Vechgama, W., Cho. J., 2023. Investigation of starting time characteristics of source term release for dissimilar nuclear accident consequence, The 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20), Washington, D.C., 20-25 August 2023.

[13] Hummel, D. W., Chouhan, S., Lebel, L., Morreale, A. C., 2020. Radiation dose consequences of postulated limiting accidents in small modular reactors to inform emergency planning zone size requirements. Ann. Nucl. Energy 137, 107062. https://doi.org/10.1016/j.anucene.2019.107062.

[14] Halfinger, J. A., Haggerty, M. D., 2012. The B&W mPower™ scalable, practical nuclear reactor design, Nucl. Technol. 178(2), 164-169. https://doi.org/10.13182/NT11-65.

[15] Zhao, L., Su, G. H., Qiu, S. Z., Wang, Z. L., 2013. Thermal–hydraulic performance analysis of IPWR during full pressure start-up mode, Ann. Nucl. Energy 60, 28-33. https://doi.org/10.1016/j.anucene.2013.04.029.

[16] Manpati, T., 2017. Knowledge politics in national nuclear energy planning in Thailand (2007-2017) with a case study of Ubon Ratchathani Province. A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Arts Program in International Development Studies, Faculty of Political Science, Chulalongkorn University, Bangkok, Thailand. https://doi.org.10.58837/CHULA.THE.2017.302.

[17] National Oceanic and Atmospheric Administration (NOAA), 2024. Weather. Available at (as of March 2024) https://www.noaa.gov/weather.

[18] Canadian Nuclear Safety Commission (CNSN), 2016. Nuclear emergency preparedness and response, REGDOC-2.10.1. Ontario, Canada. https://www.cnsc-ccsn.gc.ca/eng/acts-and-regulations/regulatory-documents/published/html/regdoc2-10-1/.

[19] United States Nuclear Regulatory Commission (U.S. NRC), 1996. Reactor site criteria, NRC Regulations 10 CFR 100. Washington D.C. https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/index.html.